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DEVELOPMENT OF DESIGN CRITERIA FOR A DRY FILM LUBRICATED BEARING SYSTEM

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by The Boeing Company, Seattle, Washington.
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FOREWORD

The research work in this report was performed by The Boeing Company, Seattle, Washington, for the Flight Dynamics Laboratory, Directorate of Aeromechanics, Deputy for Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, under AF Contract No. AF 33(616)-7395. This research is part of a continuing effort to obtain design criteria for dry film lubricated rotating power conversion equipment bearings for flight vehicles, which is part of the Air Force Systems Command's Applied Research Program 750F, Flight Vehicle Power. The Project No. is 8128 "Power Conversion and Transmission Technology", and the Task No. is 812801 "Antifriction Bearings". Paul C. Hanlon of the Flight Dynamics Laboratory was the Project Engineer. The research was conducted from 1 June 1960 to 30 November 1962 by M. E. Campbell and J. W. Van Wyk.

The authors wish to acknowledge all concerns who contributed lubricants, bearing materials and bearings for evaluation in the program. Appreciation is also especially extended to Dr. E. N. Klemgard and Mr. L. C. Lipp of Washington State University for conducting experimental research and testing in this program.

In addition to the authors, other Boeing personnel who participated in this investigation were Messers. C. S. Armstrong, R. H. Bradley, J. J. Bostjacic, J. H. Hood, P. L. Kochmstedt, R. O. Mlady, K. W. Richardson and F. Schenk.

This is the final report on the contract.

ABSTRACT

This research program was initiated to determine the extent to which dry lubricant films could be used in future bearing systems for electrical accessory applications. The program was separated into two phases.

In Phase I, twenty each, dry film lubricated 20 millimeter bore, plain, ball and roller bearings were tested in 900°F air at 15,000 rpm with a 75 pound radial and a 25 pound axial load. All available bonded dry film lubricant coatings were applied to the bearings and tested. None were satisfactory. Two different bearing designs, which used an unconventional dry film lubrication technique, demonstrated the feasibility of operation at 15,000 rpm in 900°F air.

In Phase II, roller and ball bearings were evaluated through the temperature range 70 to 1500°F at 15,000 rpm in a vacuum. The vacuum levels attained ranged between 5×10^{-4}mm Hg to 5×10^{-6}mm Hg. The initial tests in vacuum conducted on the two successful Phase I bearing designs resulted in early failures. These tests showed that the dry film lubricants, which were satisfactory in air, were entirely inadequate for vacuum operation. Therefore an investigation was initiated to develop new materials which would provide dry film lubrication under vacuum conditions. Over 400 compositions of dry lubricant and metal powders were fabricated using powder metallurgy techniques. Friction, wear, thermal expansion and fracture strengths of these materials were determined.

Thirteen roller bearing tests were conducted in vacuum using spacer rollers made from the lubricant composite materials. All tests resulted in early failure.

Conception of a new and unique bearing design utilizing lubricant composite materials as the cage resulted in successful vacuum operation for both ball and roller bearings. The roller design gave 1 hour and 25 minutes of vacuum operation at speeds of 5000, 10,000 and 15,000 rpm and temperatures of 250°F to 340°F. A test of the ball bearing design was terminated after 2 hours and 20 minutes of vacuum operation at speeds of 5000, 10,000 and 15,000 rpm and temperatures of 200°F to 680°F without bearing failure. No wear, scoring or pitting was evident in either of the roller or ball bearings after test. The new cage designs are amenable to substantial improvement through refinement of lubricant composite composition and cage design. The ball and roller tests demonstrate the feasibility of the lubricant composite cage design for high speed operation with dry lubricant films under vacuum conditions.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER

Ambrose B. Nutt

AMBROSE B. NUTT
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INTRODUCTION

Electrical accessory bearings in advanced flight vehicles will be exposed to nuclear radiation, high and low temperatures and will be required to operate under vacuum conditions.

Various efforts are being expended to obtain bearing systems that will operate in the environments anticipated for future flight vehicles. The possibility of extending the maximum operating range of organic fluids to 1500°F appears very marginal. Organic lubricants are also prone to chemical and physical change under nuclear radiation. Development programs on liquid metal lubricants and gas bearings have been initiated in attempts to solve this problem. Dry film lubrication has been used extensively for heavily loaded low speed airframe bearings. These films have also exhibited good resistance to high temperatures and nuclear radiation.

This research program was initiated to determine the extent to which dry films can be used in future bearing systems for electrical accessory applications. Dry film lubricated 20 mm bore bearings were investigated for operation in both air and 10^{-6} mm Hg vacuum, at speeds of 15,000 rpm. This program had two phases. Phase I was a feasibility program limited to 900°F. In Phase II, the feasibility of bearing operation at high speeds, light loads, in air and vacuum throughout a temperature spectrum from 250°F to 1500°F was investigated. Testing after exposure to nuclear radiation was originally included in this phase; however, due to a redirection of effort in the program this investigation was not completed.

This report is separated into three sections: (1) Phase I-900°F in Air testing of plain, ball and roller bearings, (2) Phase II-1500°F in Vacuum testing of ball and roller bearings and (3) a "Materials Section" Table LXXV which includes lubrication development conducted in both Phase I & II.

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SUMMARY

This research program was initiated to determine the extent to which dry lubricant films could be used in future bearing systems for electrical accessory applications. The program was separated into two phases.

In Phase I, twenty each, dry film lubricated 20 millimeter bore, plain, ball and roller bearings were evaluated. Testing was conducted in 900°F air at 15,000 rpm with a 75 pound radial and a 25 pound axial load. All available bonded dry film lubricant coatings were applied to the bearings and tested. None of the conventional bonded dry film coatings were satisfactory as bearing lubricants under the operating conditions investigated. Two different bearing designs, which used an unconventional dry film lubrication technique, demonstrated the feasibility of operation at 15,000 rpm in 900°F air. One design, a full complement titanium carbide cermet roller bearing, utilized ATJ graphite as a spacer roller to provide a replenishing film of graphite lubricant to the rollers and raceways. This design resulted in the lowest wear rate (0.00015 inch per hour) of all bearings tested in Phase I. The other successful bearing design was a full complement ball bearing fabricated from a titanium carbide cermet. Lubrication for this bearing was obtained from the oxide film which formed continuously on all surfaces at elevated temperatures. This bearing indicated the lowest friction coefficient ($\mu = 0.002$) of all Phase I bearings.

In Phase II, 20 millimeter bore roller and ball bearings were evaluated through the temperature range 70°F to 1500°F at 15,000 rpm in a vacuum. The vacuum levels attained ranged between 5×10^{-4} mm Hg to 5×10^{-6} mm Hg. Initial tests in vacuum were conducted on the two successful Phase I bearing designs. The roller bearing design using ATJ graphite spacer rollers did not lubricate in the vacuum environment and excessive graphite wear resulted in failure after 3-1/2 minutes of operation. The full complement ball bearing test resulted in high friction and raceway pitting after 25 minutes of vacuum operation. The lack of air prevented the formation of an oxide lubricant film. These tests showed that the dry film lubricants, which were satisfactory in air, were entirely inadequate for vacuum operation.

Therefore an investigation was initiated to develop new materials which would provide dry film lubrication for the spacer roller bearing design under vacuum conditions. Over 400 compositions of dry lubricant and metal powders were fabricated using powder metallurgy techniques. Compressive fracture strengths were determined for all specimens fabricated and over 150 friction and wear screening tests were conducted. Thermal expansion measurements were obtained for selected compositions.

Thirteen roller bearing tests were conducted in vacuum using spacer rollers made from the lubricant composite materials which were selected on the basis of the screening tests. All tests resulted in early failure due to either inadequate lubrication, disintegration of the lubricant composite materials or excessive lubricant build-up within the bearing. The longest life attained in these 13 tests was 5.7 minutes.

Conception of a new and unique bearing design utilizing a lubricant composite material as the cage resulted in successful vacuum operation for both ball and roller bearings. The roller bearing design gave 1 hour and 25 minutes of vacuum operation at speeds of 5000, 10,000 and 15,000 rpm and temperatures of [illegible]50°F to [illegible]°F with test termination resulting only from fracture of a flange on a lubricant composite segment. A test of the ball bearing design was terminated after [illegible] hours and [illegible]0 minutes of vacuum operation at speeds of 5000, 10,000 and 15,000 rpm without bearing failure although a heater element failure limited the test temperature to a maximum of 600°F. No wear, scoring or pitting was evident in either of the roller or ball bearings after test. The new cage designs are amenable to substantial improvement through refinement of lubricant composite composition and cage design. The ball and roller tests demonstrate the feasibility of the lubricant composite cage design for high speed operation with dry lubricant films under vacuum conditions.

PHASE I BEARING TESTS TO 900°F IN AIR

The following contractual requirements were specified for the Phase I program:

1. To evaluate ten dry film lubricants for use in the Phase I bearing tests.

2. To test twenty each, ball, roller and plain bearings for feasibility at 900°F, 15,000 rpm and under vacuum of 10^{-6}mm Hg.

In the Phase I program the evaluation and testing cited above were completed. A lubricant development program in Boeing Laboratories was initiated at the beginning of the contract. This lubricant development program was supplemented by a subcontract with the Washington State University. The details of the work accomplished in the Phase I effort are included in the following subsections of this report:

A. BEARING DESIGN

The following discussion outlines the bearing designs used in this program:

1. PLAIN BEARINGS

The Phase I plain bearing design was a conventional bushing with 1.10 inches O.D. and a 20 mm bore. The initial design provided a bearing width of 0.400 inches. The testing conducted during the initial report period indicated that a decrease in bearing stress of 50% would provide a significant decrease in bearing wear rate.

In discussions with the Contracting Agency a revision to the plain bearing design was presented. An increase in the plain bearing width to twice the width of a rolling element bearing was proposed. It was considered that this width increase would provide a plain bearing comparable to the rolling element bearings from a weight and envelope standpoint. This plain bearing width would provide a stress on the projected bearing area of 86 psi.

It was determined that testing plain bearings with a width greater than the rolling element bearings would necessitate extensive test equipment modification. For this reason a contract change to permit testing of the plain bearings at a stress level of 86 psi was proposed. The radial clearance was adjusted to accommodate the various lubricants being tested. This same basic design was used for all materials and lubricants tested in the Phase I plain bearing testing. The full thrust face width was used to carry the load. A drawing of this plain bearing is shown in Figure 1.

2. BALL BEARING

The design of the Phase I ball bearing was based on the current knowledge of bearings and dry film lubrication. The bearing is unique primarily because it has been designed specifically for high temperatures, high speeds, low loads and dry film lubrication.

The bearing is basically an angular contact type with larger than normal balls (3/8 inch diameter) and 56% inner and outer race curvatures. In the original design the separator was ball controlled through replaceable inserts which completely surrounded the ball. The number of rolling elements in this design was five. A drawing is shown in Figure 1. The bearing material was titanium carbide cermet for races, balls, separator and inerts.

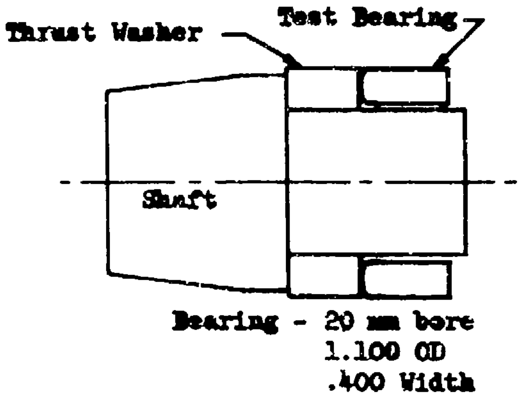
The original bearing design incorporated inserts with a 13 degree taper on the control surface. It was determined from the first two tests that this angle was not adequate. The insert was redesigned to a 25.5 degree angle.

A modification of this bearing design was investigated without a separator, but with a full ball complement. Spacer balls 0.002 inch undersize were also used. Another design modification which was evaluated, used an inner land riding No. 25 retainer.

3. ROLLER BEARING

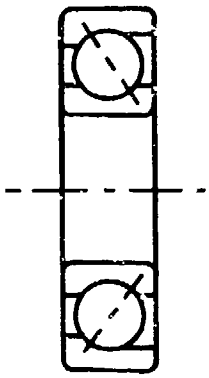
The original roller bearing design followed the same concept as the original ball bearing design cited above. It was a titanium carbide, 5 roller, double lip inner race, single lip outer race design.

The separator was roller controlled but was not of the insert type. The separator had titanium carbide pins secured to a main ring which projected into a relief at each end of the roller. The main ring was fabricated from a 0.5% titanium molybdenum alloy. The thermal expansion coefficient of this material is slightly less than that of the titanium carbide cermet K-162B. This factor was intended to maintain the press fit of the carbide pins in the main ring. Also, this design reduced sliding velocities at the control point. A drawing of the roller bearing is also shown in Figure 1.



PLAIN BEARING

Test Configuration Shaft -
TiC K-162-B
Bearing - as required
Lubricant - All sliding surfaces

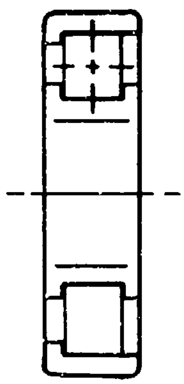


Basic 204

BALL BEARING

Test Configuration

Balls - 3/8 diameter
Race - 56% Both Races
Shoulders - 18% Both Races
Clearance - .0005 to .0010 in.



Basic 204

ROLLER BEARING

Test Configuration

Rollers - 3/8 Diameter
Shoulders - 18% Both Races
Clearance - .0005 to .0010 in.

FIGURE 1

FIGURE 1 TEST BEARING CONFIGURATIONS

Three modifications of this bearing design were evaluated. They were: (1) a slotted cage ring which was designed to provide air flow through the bearing and thereby discharge wear debris, (2) a full roller complement of carbide rollers, and (3) a full roller complement with spacer rollers acting as lubricant carriers.

B. TEST EQUIPMENT FOR 1500°F AND 10^{-6}mm Hg

The following is a discussion of the design and operation of the high speed, high temperature, high vacuum test machine. An overall view of this equipment is shown in Figure 2.

1. DRIVE SYSTEM

The prime mover consisted of a Vickers fluid motor and a Vickers hydraulic power unit with a variable volume pump. A double timing belt drive provided a total step-up ratio of 4.75 to 1. A speed of 3158 rpm of the fluid motor drove the test shaft at the required speed of 15,000 rpm. The flow through the pump was controlled manually and control of the test shaft speed was permitted through the range of 50 to 17,800 rpm. Automatic overload control was provided by the relief valve, and a by-pass valve provided a method of stopping the fluid motor. The drive system sprockets and shafts were dynamically balanced.

The system operated through all speeds satisfactorily.

2. LOAD SYSTEM

A single weight arm was designed and fabricated to apply a radial load of 75 pounds to the test bearing through a knife edge and load strap. This weight arm was modified to provide loads of 75, 37.5 and 27.5 pounds to conform with revised loads for testing plain bearings.

The load strap failed on one test because of the vibration fatigue and high temperature conditions which are unique in this test machine design. The radius on the load strap was substantially increased to eliminate stress concentrations. Operation with this modification was then satisfactory.

The dead weight system was calibrated with a dynamometer bar and provided loads with an accuracy of $\pm$ 0.5 pounds.

Axial load was applied by a cantilever strain beam and was calibrated to indicate axial load on the test bearing directly in pounds.

3. FRICTION MEASUREMENT

Friction was measured with two linear cantilever strain beams that restrict the rotation of the load strap beam about the knife edge. Friction readings were reported on a Bristol recorder. The reading on the recorder

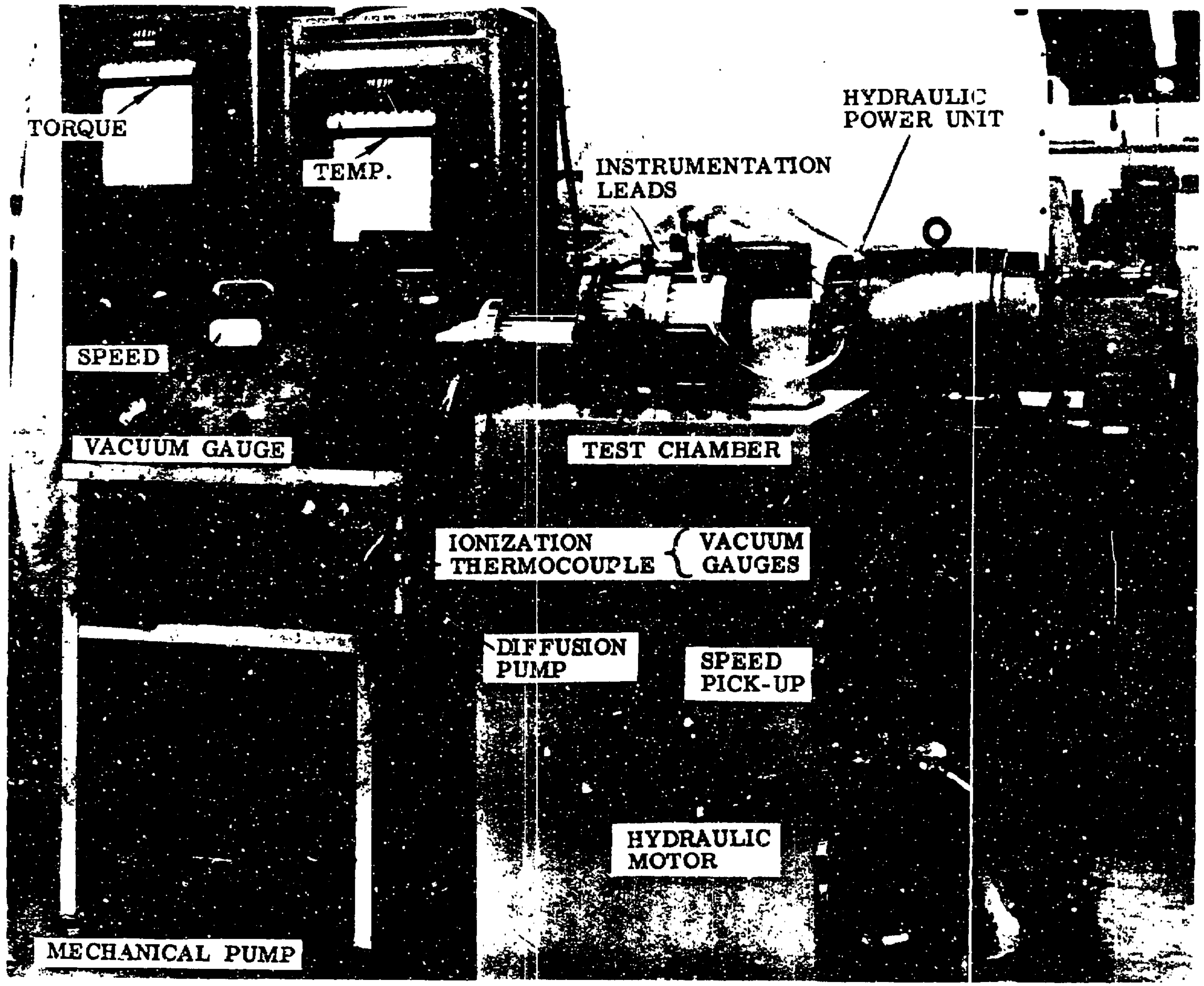


FIGURE 2 BOEING TEST MACHINE

was precalibrated (for sensitivity, load and bearing size) to indicate coefficient of friction value directly.

4. HEATING SYSTEM

Bearing temperatures of 900°F and 1500°F in air were obtained with a nichrome wire resistance heater located on both sides of the test bearing. A single heater was used for plain bearing tests. With two heating elements, the temperature gradient across the outer race of antifriction bearings did not exceed 15°F.

Tantalum wire of the same diameter as the nichrome has been used satisfactorily for tests in vacuum at 900°F.

5. VACUUM SYSTEM

The vacuum system consisted of a mechanical pump and a 4 inch diffusion pump connected to a cold trap. This system produced pressures as low as 1×10^{-6}mm of Hg. With neoprene lip seals installed and the shaft rotating at 15,000 rpm, a vacuum of 5×10^{-5} was held over a period of one hour. Viton A and Teflon seals provided the same pressure performance, but with less wear.

A spring loaded graphite face seal with the inner race of the bearing as a sealing face was used for testing ball and roller bearings. The pressure increased to 50 microns on the first test due to poor lubrication of the seal, but a vacuum of 2 times 10^{-5} was attained on the second test using an increased supply of 702 fluid as a lubricant.

C. BEARING TEST RESULTS AND ANALYSIS

The bearing testing was intended to provide a basis for comparison of the plain, ball and roller types of bearings. The conditions included in this evaluation were 900°F temperature and a shaft speed of 15,000 rpm. The details of the screening tests, the apparatus and procedures are described in the Materials Section of this report. A summary of the results of these tests is included in Table VIII of this report. In addition to obtaining comparative dry film performance data, this testing provided design criteria applicable to the high speed dry film lubricated plain bearing.

1. PLAIN BEARINGS

Initial testing was conducted on the plain bearings to provide an improved basis for dry film selection. The dry films selected in the screening program were initially applied to titanium carbide cermet K-162B bearings and shafts. Upon completion of these tests, selected dry films were evaluated as applied to other refractory and superalloy materials. The best bare material and dry film combinations were then used in the ball and roller bearing tests.

The plain bearing tests and results are tabulated on Table I. Plain bearing wear rates are plotted in Figure 3.

All initial plain bearing tests were conducted at 15,000 rpm and 900°F initial ambient air temperature. A 25 pound axial load and a radial load, which produce a projected bearing area stress of 86 psi, were applied. Final plain bearing tests included operation in 5×10^{-5}mm Hg pressure.

The unlubricated bearing tests P-1, P-2 and P-3 failed by seizure. All failures were the result of scoring and seizure on the thrust face of the test bearing. This type of failure illustrated the significant effect of clearance on bearing performance. The unlubricated bearings tested with radial load only operated for periods of 50 minutes without seizure. Seizure was experienced only when the bearing had insufficient clearance. It is considered that modifications of the thrust face design would improve unlubricated plain bearing performance.

Lowest plain bearing friction was obtained with the graphite No. 2573 material used in test P-4. The seizure which occurred in this test was not the result of scoring or galling. Due to the low thermal expansion coefficient of the No. 2573 bearing relative to the carbide shaft, the bearing radial clearance decreased during operation. A circumferential seizure was evident. The initial graphite No. 2490 bearing scheduled for test P-5 fractured during press fit installation into the carbide housing. A new bearing was fabricated for this test. After one hour and twenty minutes the test was terminated due to excessive wear. The temperature increased to over 1800°F in this test.

The best plain bearing performance (17 hours 1 minute) was obtained in test P-6. The test specimen was a carbide bearing and shaft which had a phthalocyanine dry film coating. The details of this coating application and procedures are described in the Materials Section of this report. The bearing temperature in this test increased from an initial value of 900°F to 1200°F in 11 minutes. The temperature fluctuated between 1200°F and 1300°F for the majority of test duration. Occasional temperature fluctuations were noted between 1100°F and 1500°F for periods of 10 seconds or less.

TABLE 1

PLAIN BEARING TEST SUMMARY

TEST NO.	BEARING MATERIAL	LUBRICANT	TEMP. °F START	TEMP. °F MAX.	RPM	INCHES INITIAL PLAY	FRICTION START	FRICTION RUN	LIFE	INCHES WEAR BEARING	INCHES WEAR SHAFT	RADIAL PLAY INCREASE IN./HR.	REMARKS
P-1	K162B	None	70	1600	14,000	.0035	.6+	----	15 sec.	--------	-----		Seizure - Scored
P-2	K-162B	None	900	----	------	.0037	.6+		15 sec.	--------	-----		Seizure - Scored
P-3	Al_2O_3 61170	None	70	----	------	.0029	.80+	----	5 sec.	--------	-----		Seizure - Scored
P-4	Graphite 2573	None	900	900	15,000	.0037	.22	.08	6 min.	.0003	.0000	.003	Seizure - Not Scored
P-5	Graphite 2490	None	900	1800	15,000		.28	.07 .14	1 hour 20 min.				
P-6	K-162B	Phthalocyanine	900	1240	16,000	.0033	.30	.25	17 hours 1 min.	.0060	.0047	.00063	Test Terminated Excessive Wear.
P-7	K-162B	Hohman M-1284	900	1000	12,000	.0027	.29	.13	60 sec.	--------	-----		Seizure - Cracked Bearing
P-8	K-162B	MoS_2 PbS Midwest	900	1170	14,100	.0031	.25	.15	2 min 15 sec.	--------	-----		Seizure - Scored
P-9	K-162B	Bi_2O_3	900	1620	15,500	.0035	.42	.15	1 hour 47 min.	.0027	.0029	.0031	Seizure - Scored
P-10	K-162B	NASA CaF_2	900	1600	15,000	.0032	.35	.28	20 min.	.0006	.0002	.0024	Excessive Friction
P-11	SIC	Phthalocyanine	900	1510	15,000	.0031	.23	.15	2 hours 23 min.	--------	.0005		Fractured Bearing
P-12	Star J	Phthalocyanine	900	1520	15,000	.0040	.18	.04 +.32	3 min. 40 sec.	.0004	.0000	.0065	Excessive Friction
P-13	LT-1	Phthalocyanine	900	1620	15,000	.0030	.22	.14	1 hour 21 min	0062	.0005	.005	Seizure - Scored
P-14	Graphite 2490	None	900	1800+	15,000	.0045	.28	.072 to .145	1 hour 20 min.	.012	.0003	.0092	Inconel X Thrust Face - TIC Shaft
P-15	Al_2O_3	Graphite & Silver	900	1800+	16,000	.0047	.30	.21	20 min.	.0002	.003	.0096	Friction Increased to .35+
P-16	Al_2O_3	Phthalocyanine	900 900	1440 1440	15,000 15,000	.0060 .0060	.14 .14	.16 .16	1 hour 1 hour	.0008 .0008	.0001 .0001	.0008 .0008	Thrust face Cracked Thrust Face Cracked
P-17	Nickle Alloy	Phthalocyanine	900	1560	15,000	.0031	.30	.08 .16	13 min.	.0040	.0002	.0194	Bearing housing Broke
P-18	Nickle Alloy	Phthalocyanine	900	960	15,000	.0044	.32	.05	2 min. 35 sec.	.0012	.0000	.0288	Drastic Increase In Friction To .30
P-19	TIC	Phthalocyanine	600	1280	15,000		.244	.090	3 min.				3 to 1 x 10^{-4} vacuum-bearing seized
P-20	Al_2O_3	Phthalocyanine	1150	1700	15,000		.240	.100	60 min.	.0011	.0007	.0018	Air-Coors B1170

NOTE: All plain bearing tests conducted with an 86 psi radial load, 25 lbs. thrust load and a 20 mm K-162B titanium carbide shaft.

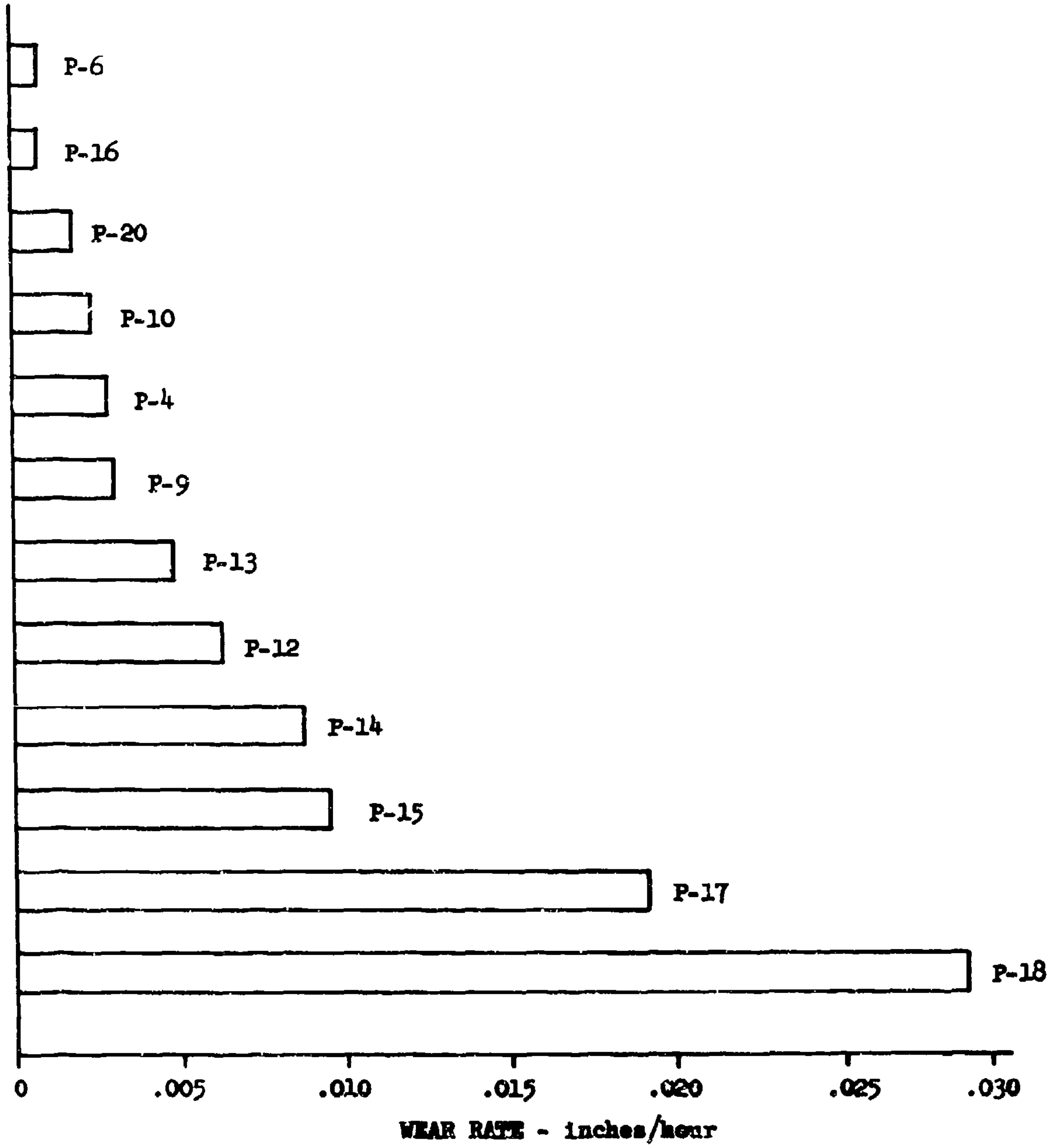


FIGURE 3 PLAIN BEARING TESTS - WEAR RATES

The load strap failed in fatigue after 4 hours and 8 minutes of test operation. During the following down time the test bearing was removed for examination. All loaded surfaces were highly burnished over approximately 2/3 of the surface area. The remaining 1/3 of the area was covered with streaks of a light yellow powder. (See Figure 4) An x-ray diffraction and spectrographic analysis of the powder was made on completion of this test. The material was mainly a combination of rutile (TiO_2) and nickel oxide (NiO) in the ratio of two to one. Wear measurements obtained during this examination indicated wear of .0004 to .0006 inches on all surfaces. During the restart of this test the friction coefficient indicated an instantaneous value of 0.5. When maximum speed was attained the coefficient decreased to 0.28. For the remaining 12 hours and 53 minutes of test the friction coefficient gradually decreased to 0.22. See Figure 5 for a replica of selected friction recordings obtained during this test.

A failure in the hydraulic power unit caused the test shutdown after a total operating time of 17 hours and 1 minute. The test bearing was again removed for examination. All load zone surfaces were similar in appearance to their condition after the initial 4 hour and 8 minute run. See Figure 4 for photograph. Wear measurements obtained after this test indicated the following:

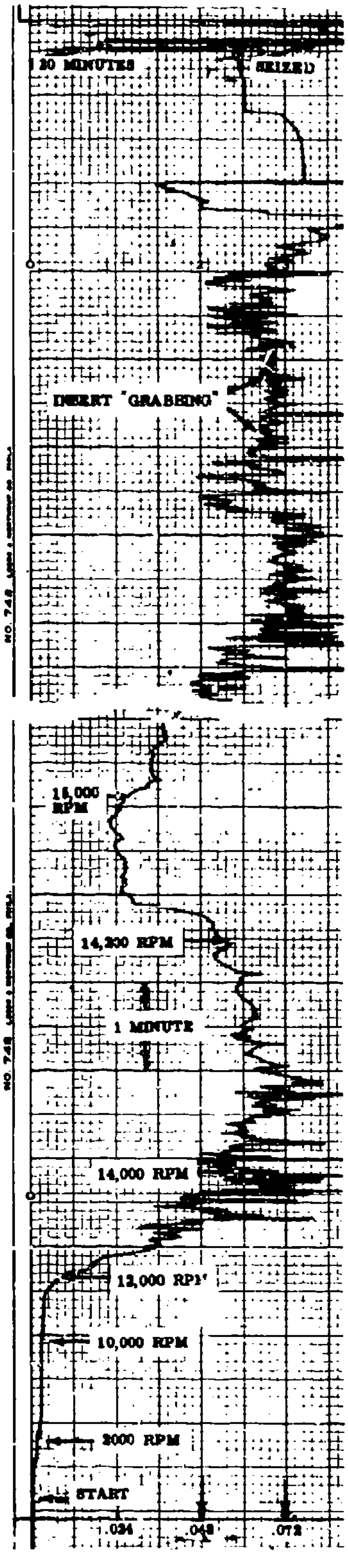
Bearing radial wear	.0060 inch
Shaft radial wear	.0047 inch
Total radial wear	.0107 inch
Bearing thrust face wear	.0100 inch
Shaft thrust face wear	.0040 inch
Total thrust wear	.0140 inch

Since the wear had exceeded the allowable .010 inches, the test was terminated. However, when the wear was calculated in inches per hour, this test had the lowest wear rate of the plain bearing tests. (Figure 3)

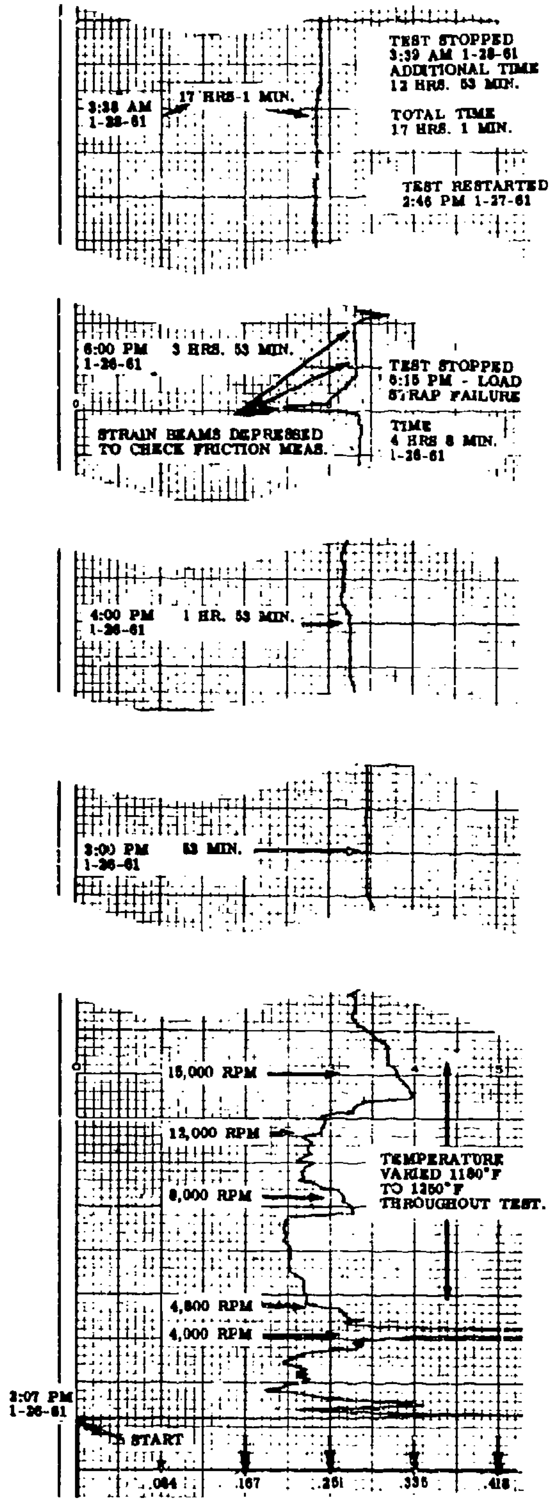
The M-1284 dry film coated carbide bearing was fractured during test P-7. In this test the temperature increased due to frictional heating from 900°F to 1500°F in 15 seconds. The thermal stresses introduced are considered to have caused the fracture. A sharp edge on the fracture produced light score marks on the shaft. No scoring was evident on the thrust face.

PHTHALOCYANINE COATED PLAIN BEARING AFTER 17 HRS.-1 MINUTE @1200°F-15,000 RPM. NOTE YELLOW POWDER ON SHAFT END AND BUSHING BORE.

FIGURE 4 TESTED PLAIN BEARING



BALL BEARING TIC-INSERT
TYPE UNLUBRICATED. TEST B-1



PLAIN BEARING TIC-BUSHING SHAFT
PHTHALOCYANINE COATING. TEST P-6

FIGURE 5 FRICTION CURVES FOR BALL AND PLAIN BEARINGS

The intense frictional heating at the thrust interface is considered to be the main cause of failure in test P-8. The dry film coating, a 4:8:1 ratio of MoS_2, PbS and H_3BO_3 failed to maintain the bond to the carbide as the temperature increased. A maximum temperature of 1170°F was recorded at the time of seizure (2 minutes, 15 seconds).

For test P-9, a .001 dial indicator was located on the radial load arm to provide an indication of bearing radial wear during test. A high wear rate was noted during the first 5 minutes of test. About .003 inch radial wear was indicated. For the remainder of the test the wear rate was essentially uniform with a total radial wear of .005 inch indicated just prior to seizure.

The temperature increased from the 900°F start to a 1500°F operational temperature in six minutes. The temperature then essentially stabilized at 1500°F ± 50°F for the remainder of the run. During the final 5 minutes of operation the degree of temperature fluctuation increased to a peak value of 1620°F. The measured total radial and axial wear after test was .0056 and .0029 inches respectively.

In test P-10 the bearing and shaft were coated with the NASA developed calcium fluoride dry film. Excessive friction was indicated during the test run. Examination of the bearing surfaces after test revealed scarred and pitted areas. A deleterious chemical reaction may have occurred between the fluoride and the carbide materials.

Test P-11, a KT silicon carbide plain bearing coated with a phthalocyanine film represented the second most successful plain bearing performance. It operated for 2 hours and 23 minutes compared to 17 hours and one minute for test P-6. The eventual failure of test P-11 bearing is believed to have been initiated by a crack in the thrust face. Both the bore of the bearing and the thrust surfaces showed a smooth burnish and a thin oxide layer. Wear measurements were impossible due to the nature of failure.

Tests P-12, P-17 and P-18 were tests of phthalocyanine coated superalloy bearings (Star J, nickel alloy 500 and nickel alloy X) on titanium carbide shafts. In each instance a high bearing wear rate was evident. These tests show a direct correlation between bearing wear and material hardness. Accordingly, the high hardness Star J material exhibited the lowest wear rate and the nickel alloy X the highest. (Figure 3)

In test P-13 a chrome-alumina material, LT-1, was evaluated with a phthalocyanine film. After 1 hour and 21 minutes of test the bearing seized on the shaft. Wear measurements indicated that the majority of wear (0.0062 inches) occurred on the test bearing. Only 0.005 inch shaft wear was measured.

High frictional heating occurred in test P-14. The temperature rose to 1800°F after a radial wear of .010 inch had occurred on the graphite bearing material. At the .010 inch wear condition, nickel alloy X thrust washer contacted the carbide shaft with a resulting higher friction and temperature reading. Prior to .010 inch wear condition, the temperature had stabilized at 1060°F.

In test P-15 a porous aluminum oxide bearing material (AP-100) was impregnated with silver which was coated with graphite. In this test, temperatures in excess of 1800°F and a friction coefficient of .21 were indicated. The shaft wear rate, .009 in./hr., was the third highest of all plain bearings tested. Examination of the shaft and bearing wear debris after test indicated the possibility of chemical reaction between the carbide shaft and the silver bearing matrix.

In test P-19 a phthalocyanine coated carbide bearing and shaft were tested in a vacuum of 5×10^{-5}mm Hg. Extensive outgassing was visible within the test chamber as the pressure approached 1×10^{-3}mm Hg. After 3 minutes of operation a permanent bearing to shaft seizure occurred. Examination of the bearing after test revealed that the phthalocyanine coating had been removed from all areas of the bearing and shaft during the outgassing period in the vacuum. In an attempt to remove the test bearing from the shaft, the bearing fractured. The welding of the bearing to shaft was very severe. A carbide section about 3/16 inch diameter by 1/16 inch deep was pulled away from the shaft during bearing removal.

Due to the ineffectiveness of the phthalocyanine coating in test P-19 under vacuum conditions, test P-20 was conducted in air. This test was a repeat of the materials used in test P-16. The bearing material was B-1170 aluminum oxide. The shaft was titanium carbide cermet. Both were coated with a phthalocyanine film. In order to evaluate the effect of Phase II environment, the bearing temperature prior to start of shaft rotation was increased from the P-16 temperature of 900°F to 1150°F. This higher starting temperature resulted in an operating temperature of 1700°F for this test. This was 260° higher than test P-16. Wear measurements after test on test P-20 were higher than P-16 for both bearing and shaft. (Figure 3) This factor substantiates previous investigations which have indicated the upper temperature limit for the phthalocyanine film at 1500°F.

Tests P-16 and P-19 had the second and third lowest wear rates of the plain bearings tested. (Figure 3) This is attributed to the wear resistance of the B-1170 aluminum oxide bushing.

2. BALL BEARINGS

Twenty-one ball bearing tests were conducted in the Phase I program. A description of the bearing designs, lubricants and test results are tabulated in Table II. Wear rates are compared in Figure 6.

TABLE II

BALL BEARING TEST SUMMARY

Titanium Carbide Races and Balls - 15,000 RPM - 75 lbs. Radial - 25 lbs. Thrust

TEST NO.	CAGE DESIGN	LUBRICATION	CLEARANCE INITIAL	CLEARANCE FINAL	FRICTION START	FRICTION RUN	TEMP. °F START	TEMP. °F MAX.	LIFE MIN.	RADIAL PLAY INCREASE IN./HR.	REMARKS
B-1	Old Insert	None	.0004	.0013	.002	.03	70	1060	22	.0025	Severe Insert wear and grabbing.
B-2	Old Insert	M-1284	.0003	.0003	----	----	70	----	3	0	Inserts wedged on balls - 7,000 RPM max.
B-3	New Insert	Poly Phenyl Ether	.0004	.0012	.006	.002	70	940	9	.0051	Oil at start - rough when oil decomposed.
B-4	New Insert	Pre-Oxidized	.0005	-----	.006	.015	900	940	1	-----	O. R. fractured.
B-5	New Insert	Pre-Oxidized	.0006	-----	.002	.010	900	920	7	-----	O. R. fractured - shaft disengaged.
B-6	New Insert	Phthalocyanine	.0004		.009	.005	900	900	33	-----	Rough friction - stopped for inspection.
B-7	New Insert	Phthalocyanine		.0076	.015	.009	900	950	30	.0060	B-6 rerun - rough friction.
B-8	New Insert	Graphite Insert	.0004	.0011	.003	.006	900	930	2	.0210	Inserts fractured.
B-9	New Insert	Phthalocyanine	.0005	.0135	.016	.011	900	1050	135	.0046	40 thrust - 38 radial - Insert fractured.
B-10	New Insert	PbO	.0004		.001	----	900	915	1	-----	Insert grabbed.
B-11	Full Comp.	PbO		.0137	.002	.007	900	950	60	.0133	B-10 rerun - axial wear - stopped for inspection.
B-12	Full Comp.	811	.0004		.001	.009	900	950	92	-----	Smooth running - axial wear.
B-13	Full Comp.	Pre-Worn		.0208	.037	.010	900	950	72	.0075	B-12 rerun - smooth running - wear.
B-14	Full Comp.	None	.0005	.0025	.009	.013	900	950	40	.0031	80 thrust - 8 radial - erratic friction.
B-15	I.R. Con.	M-1284	.0004	.0269	.001	.012	900	980	255	.0062	Excessive Wear.
B-16	Full Comp.	811	.0025	.0093	.001	.006	900	960	120	.0034	B-14 rerun 80-8 load.
B-17	I.R. Con.	M-1284	.0006	.0048	.002	.013	900	1030	6	.0420	80-8 load - erratic friction - rapid wear.
B-18	Full Comp.	None	.0005	.0008	.001	.007	1475	1500	60	.0003	Very smooth - low friction - glazed surfaces.
B-19	Full Comp.	None	.0007	-----	.002	.002	800	1050	30	Low	2×10^{-5} mm Hg pressure - I.R. fractured - no wear.
B-20	Full Comp.	None			.002	----	800	1080	34	-----	4×10^{-5} (running friction inaccurate) TiC spacer balls to 5 microns vacuum.
B-21	Full Comp.	None			.019	.008	900	1230	25	-----	Friction increased to .025 1×10^{-4} to 2×10^{-5} vacuum.

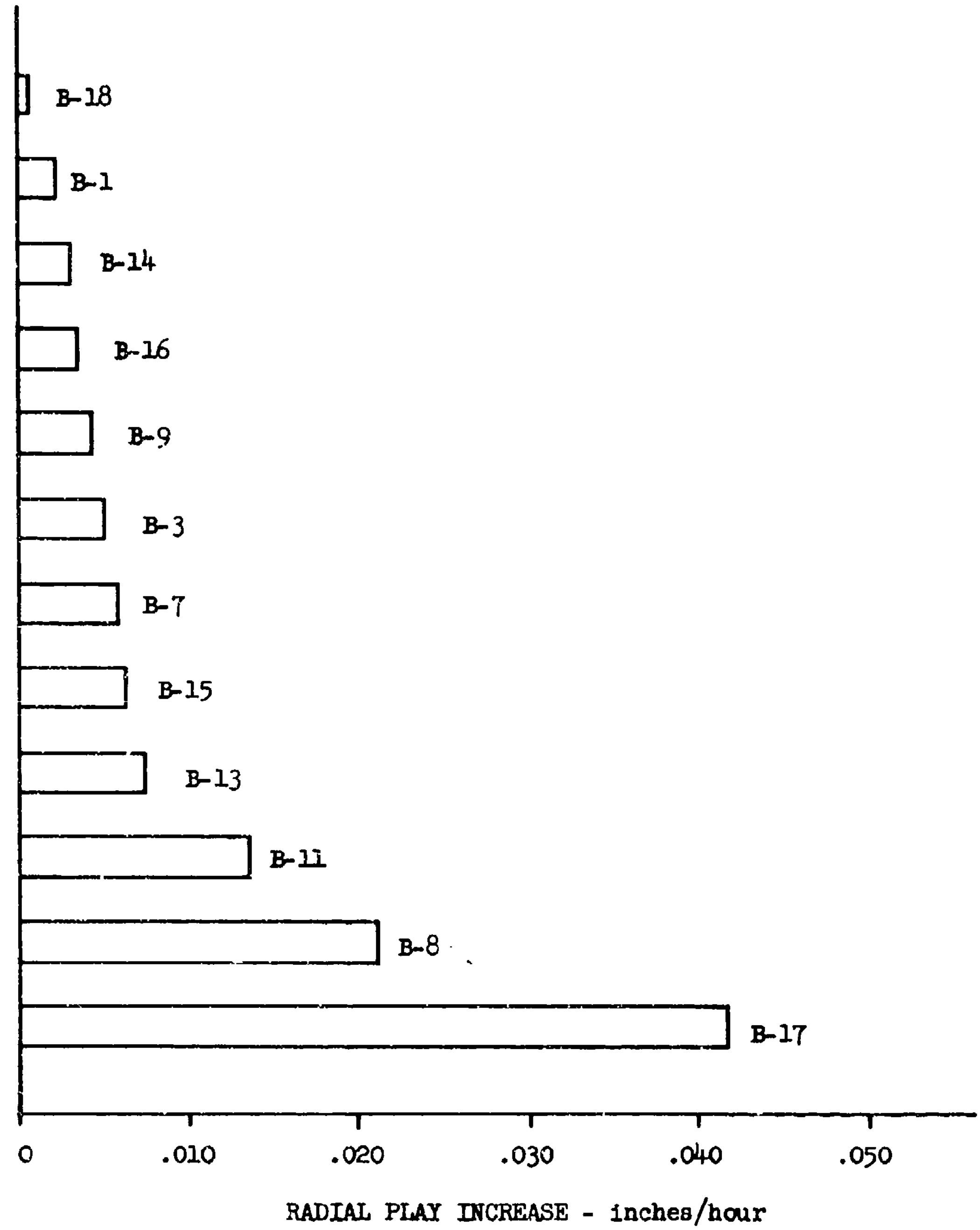


FIGURE 6 BALL BEARING TEST - WEAR RATES

The first bearing tested (test B-1) was unlubricated. It was tested at room temperature in air. The bearing operated for 22 minutes at 15,000 rpm. The test was stopped due to a rapid friction rise caused by the master cage ring coming in contact with the inner race. In the process of testing the outer race temperature increased to 1060°F. The balls were visibly "red hot".

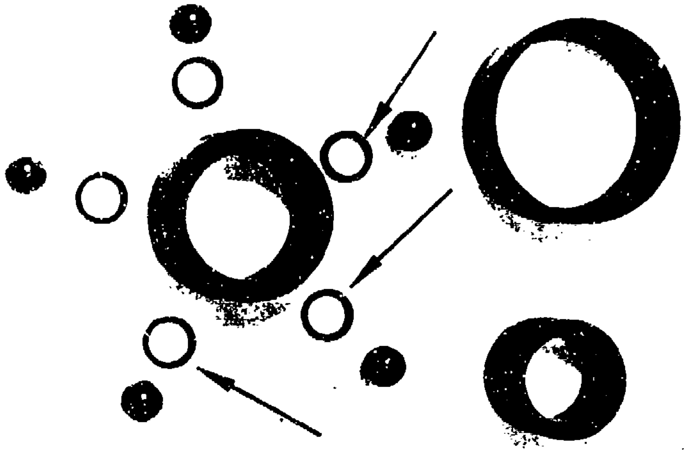
Upon inspection it was evident that the inserts had worn severely causing reduced separator control and allowing contact with the inner race. The erratic friction curve shown in Figure 5 is believed to be the result of the inserts periodically "grabbing" the balls. The balls however, had no measurable wear. Inner and outer raceways were in good condition showing only discoloration of the ball track. This bearing had the second lowest wear rate of the ball bearings tested. (Figure 6) A photograph of this test bearing is shown in Figure 7.

The second test bearing (test B-2) had M-1284 dry film lubricant on the inserts only. This bearing operated with erratic friction from the start and ran for 3 minutes. Due to the varying friction level the bearing was accelerated slowly and reached only 7000 rpm after three minutes. Inspection showed that two inserts had locked onto the balls. All inserts showed wear. Balls and raceways appeared to be in excellent condition.

It was concluded that increased taper of the inserts was required to eliminate "grabbing" tendencies.

Test B-3 was conducted using the redesigned lower angle inserts. The bearing was started with approximately two drops of phenyl ether fluid in the bearing. As the temperature increased, the fluid evaporated and the bearing became unlubricated. The bearing ran a total of 9 minutes 30 seconds. Approximately 8-1/2 to 9 minutes of this period the bearing had some lubrication. While lubricated, the friction increased to .06 and was erratic.

The reason for the failures in tests B-4 and B-5 were not evident until completion of test B-8. The location of the outer race fractures in B-4 and B-5 indicated that a high moment load had been applied to the bearing. It was considered that the original design of the test spindle was the cause for the moment loading. During operation, the thermal expansion of the steel spindle shaft was greater than that of the carbide stub shaft. As a result, it was believed that the following sequence occurred: (1) the self-locking taper on the stub shaft became loose, (2) the stub shaft then misaligned relative to the outer race causing moment loading in the bearing and resulting failure, (3) the tests were stopped and radial load removed, (4) thrust load still on the bearing reseated the stub shaft due to the absence of radial load, (5) cooling caused the stub shaft to become locked in position thereby presenting a



TITANIUM CARBIDE BALL BEARING AFTER 22 MINUTES RUN. NOTE CRACKED INSERTS CAUSED BY INSERT GRABBING

FIGURE 7 TESTED BALL BEARING

completely normal appearing assembly upon bearing removal. This automatic reseating of the assembly misrepresented the actual condition and prevented immediate recognition of the problem. This condition was corrected. In all subsequent tests the stub shaft was anchored to the steel spindle with a bolt through the shaft.

It is believed that this problem did not occur in the plain bearing tests due to two factors: (1) higher stub shaft temperatures and heat rates caused by direct sliding friction, and (2) lower moment load on the stub shaft due to the reduced radial load.

In test B-6 a phthalocyanine film was applied to the carbide raceways and cage inserts. After 33 minutes of operation the bearing friction increased and became erratic. The test was stopped for bearing inspection. The examination indicated light wear on the cage insert rings and a light powder wear debris within the bearing. An air blast applied to the bearing removed the wear debris and the bearing turned freely. This bearing was reinstalled for test B-7. After an additional 30 minutes of operation, the friction again increased and the test was terminated. Examination of the B-7 bearing revealed the powdered wear debris similar to that obtained in test B-6.

Two ball bearings were tested under a predominate thrust load (40 lb. thrust, 37.5 lb. radial) to determine the effect of changing the load direction. The first bearing (test B-9) operated with phthalocyanine coated races, balls and inserts, ran for 2 hours, 51 minutes. The bearing was smooth running but generated considerable wear debris. Ultimate failure was caused by fracture of an insert ring. Ball wear was .0025 inch. A second bearing, test B-10, coated with lead oxide (except the balls), operated for only 1 minute. The inserts grabbed the balls and caused high erratic friction. This grabbing tendency was believed to be caused by slight unevenness of the lubricant coating on the inserts. These tests illustrated the design sensitivity of the insert cage. Throughout the testing it has been extremely important that uniform coatings be applied and that selective assemblies be made for individual ball pockets.

Discussions with Stratos personnel who were conducting a 1200°F bearing program (AF 33(616)-6589), revealed a somewhat surprising result with a full complement bearing operating at room temperature. It was reported that this bearing operated for one hour at approximately 500,000 DN. It was agreed by Stratos and this Contractor that continuous lubrication accounted for the relative success of this bearing.

A similar full complement bearing was tested in this program. The bearing from test B-10 was assembled with spacer balls from test B-9 and tested under the normal 75 lb. radial-25 lb. thrust load. This bearing (test B-11), operated at extremely low friction and required 30 to 40% heating unit power to maintain 900°F. Wear was quite rapid for approximately 10 to 15 minutes but increased very little beyond that point. The bearing was stopped after 1 hour for inspection. It was found that wear on the load balls and spacer balls was .002 to .003 inch each. Radial wear was .0020 inch on the inner race and on the "heavy load" zone of the outer. Raceway curvatures had worn to approximately 50.5 to 51% in the wear track. The heavy initial wear was attributed to the wide curvature of the original bearings.

One test (B-12) was run with a full complement bearing having 10 full size balls. The races were coated with 811 lubricant. The bearing ran 1 hour, 32 minutes, and exhibited nearly identical performance and wear as test B-11 above.

The raceways used in Test B-12 were reassembled with new balls for test B-13. In this test the effect of bearing performance with the increased conformity of the worn raceway was investigated.

A decrease in wear rate over test B-11 was experienced. (See Figure 6)

Test B-14 was conducted to determine the effect of increasing the ratio of axial to radial load. An 80 pound axial and an 8 pound radial load were used. These loads produced the same resultant load on the bearing as the previous 25 pound axial and 75 pound radial load. As expected, the radial wear rate decreased significantly. (Third lowest in Figure 6) Axial wear was higher than anticipated (in excess of .050 inch) and erratic friction was evident through the test run. Examination of the raceways after test revealed raceway conformity which was 50.5 to 51% of the ball diameter in the wear track. The high axial wear and erratic friction was attributed to the low initial conformity and lack of lubrication.

Due to sensitivity of the insert cage it was decided that a more conventional land riding retainer would be tested. Retainers were made from Alloy No. 25 with pocket and land clearances, .005 inch and .010 inch respectively, determined suitable in the Stratos 1200°F bearing program (AF 33(616)-6589).

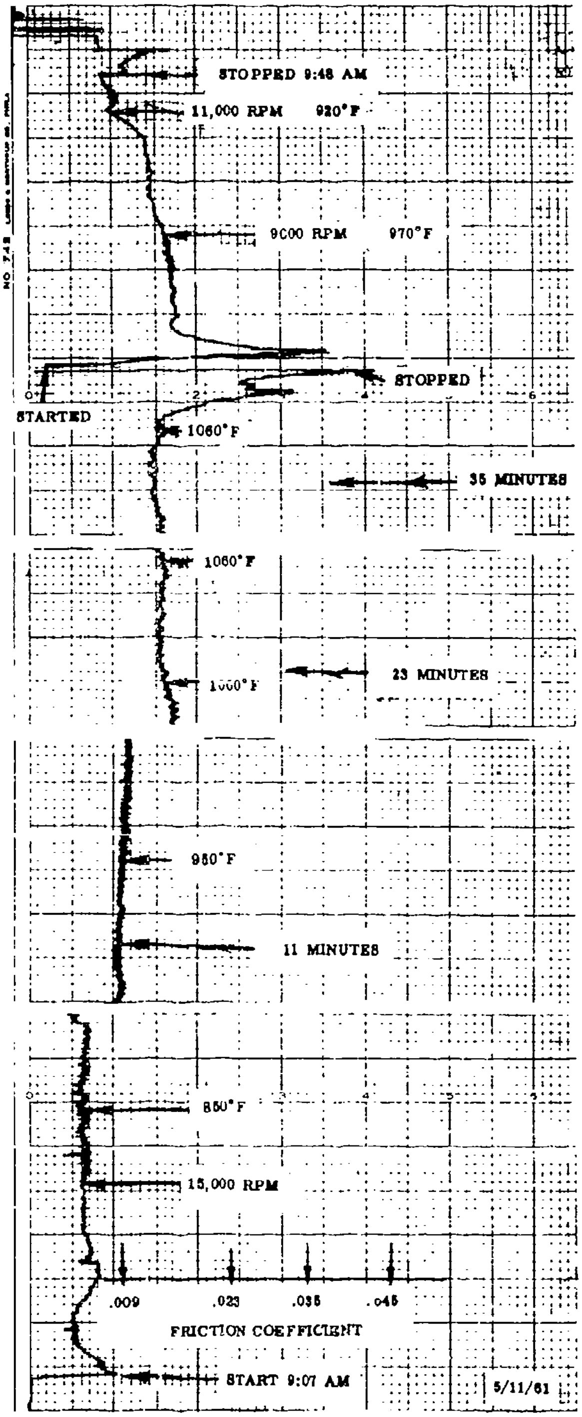
In test B-15 the inner land riding Alloy No. 25 retainer was evaluated. The raceway and retainer were coated with M-1284 dry film prior to test. The bearing operated for 4 hours and 15 minutes. A high axial wear and a high radial wear rate (.0065 inch/hour) were obtained in this test. The test was terminated due to an increasing frequency of high torque indications. Examination of the bearing showed inner and outer land contact of the retainer. Light scoring was evident on the retainer contact zones. Approximately .004 inch to .006 inch ball pocket wear was evident in the retainer.

The "conforming" raceways obtained in test B-14 were coated with another dry film lubricant (811) for evaluation in test B-16. An 80 pound axial and an 8 pound radial load was applied. This test was run for 120 minutes. The test produced essentially the same wear rate obtained in test B-14. (Figure 6) No apparent improvement in performance was obtained with the increased conformity or with the dry film lubricant.

Test B-17 was conducted with the land riding alloy 25 M-1284 dry film lubricated retainer under the 80 pound axial and 8 pound radial load. This test resulted in the highest wear rate of all ball bearing tests conducted in Phase I. (Figure 6) This factor may be attributed to the short test time (6 min.) and the probability of a high initial wear occurring during the initial minutes of operation.

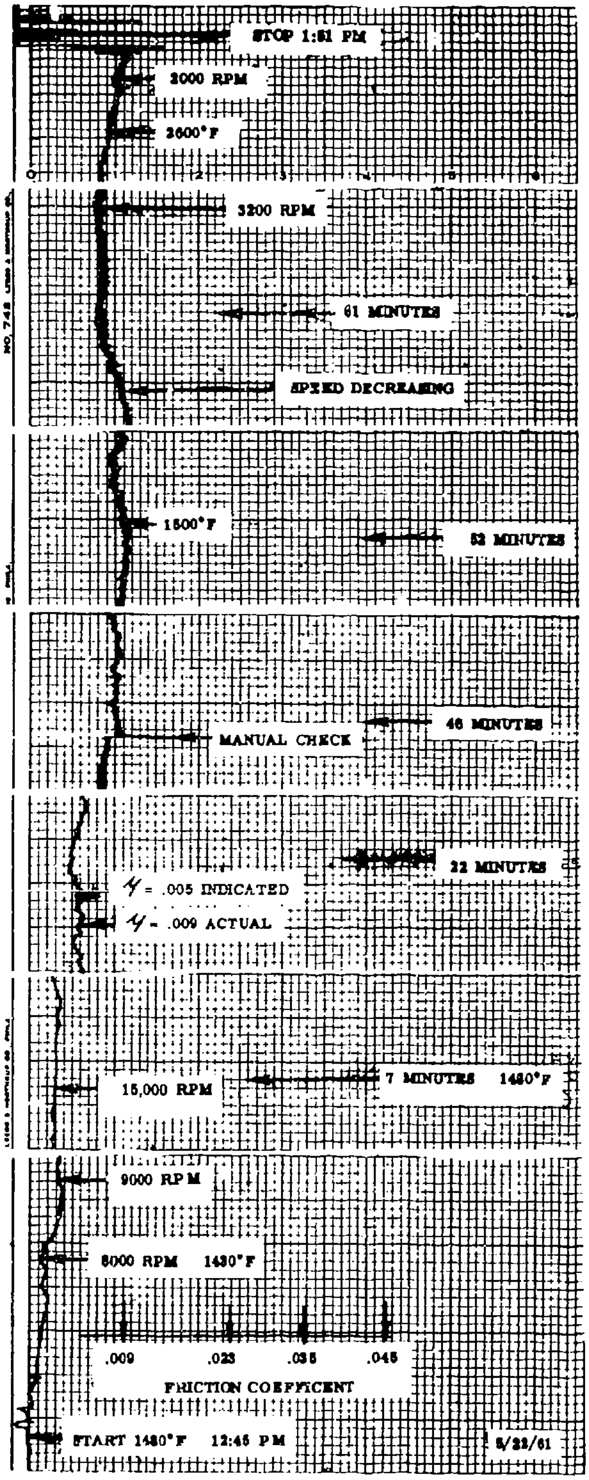
Test B-18 was conducted at 1500°F to obtain preliminary performance data at the Phase II temperature condition. The bearing was full complement with .002 inch undersize spacer balls. The spacer balls had been pre-oxidized and worn undersize in a previous test. The bearing exhibited low friction throughout the 60 minutes of test time. After 60 minutes, the bearing was removed for examination. The lowest wear rate (.0003 inch/hour) of all ball bearings tested was obtained in this test. (Figure 6) The balls and raceways were highly polished and exhibited a glazed oxide film. This test demonstrated the effectiveness of lubrication by the oxide film. Oxide film lubrication in this test correlates with the low wear rate of the carbide plain bearings which operated at the higher temperatures. The thermal gravimetric analysis of the carbide (see Figure 31) indicates the rapid formation of the oxide film only above 1400°F. This factor accounts for the higher wear rate of an identical full complement bearing test B-14 at the 900°F test temperature. The thermal gravimetric analysis also indicates the probability of satisfactory oxide film formation at temperatures above 1500°F. A reproduction of the frictional torque recording for this test is in Figure 8.

The test B-19 bearing was identical to the low wear rate full complement bearing evaluated in test B-18. The test conditions were changed to the 900°F temperature and operation in a vacuum. The bearing operated for a 30 minute time period during which a vacuum of 2×10^{-5}mm of Hg was obtained in the test chamber. After 30 minutes of test time, a gradual friction increase attained a sudden peak value. At this point the test was terminated. Examination of the bearing showed a circumferential inner race fracture in the wear track and no significant wear of the raceways or balls. Minute surface deterioration of the raceways was evident. Fracture of the inner race in this test was attributed to the high stresses produced by thermal expansion of the inner race. Score marking on the bearing bore and on the shaft indicated extensive shaft rotation. It was considered that the frictional heating produced by shaft slippage in the bore was of sufficient magnitude to cause the subsequent inner race fracture.



TEST R-14 ROLLER BEARINGS (NO CAGE) ATJ GRAPHITE SPACER ROLLERS DIPPED IN GRAPHITE SOLUTION.

75# RADIAL LOAD 25# AXIAL LOAD



TEST B-18# BALL BEARING (NO CAGE)

75# RADIAL LOAD 25# AXIAL LOAD

FIGURE 8 FRICTION CURVES FOR BALL AND ROLLER BEARINGS IN AIR

Test B-20 was a repeat of the B-19 bearing configuration and test conditions (900°F and vacuum). In order to prevent shaft rotation in the bearing bore, the bore was electroless nickel plated to provide a shaft fit of 0.0002 inch interference. The bearing was operated for 34 minutes. During the final minutes of this test a gradual friction increase was evident. A variation in vacuum between 5 microns and 4×10^{-5}mm Hg was obtained throughout the test period. The test was terminated at a friction value below that which produced inner race fracture in test B-19. Upon examination after cooling the bearing indicated relatively low friction characteristics. After this test, it was determined that the bearing torque measurement strain gage was in error.

In order to obtain an accurate friction indication, the bearing tested in test B-20 was reinstalled in the test machine for test B-21. After 25 minutes of operation in a vacuum, which ranged between 1×10^{-4} to 2×10^{-5} mm Hg, the test was terminated. A gradual friction increase was evident throughout the test period. Examination of the bearing revealed no significant wear, but minute surface deterioration in the wear track. A light build up of wear debris in the wear track was evident. The bearing was tight and "sticky" when rotated by hand. A friction-life chart for this test is shown in Figure 9.

3. ROLLER BEARINGS

A total of twenty titanium carbide roller bearings were tested during the Phase I program. The results are tabulated in Table III. Wear rates are compared in Figure 10.

Three basically different roller bearing configurations were evaluated in tests R-1 through R-11. The base line configuration is referred to as the pinned cage. This cage consists of a roller controlled separator with titanium carbide pins extending into holes in the roller ends.

The second configuration is a modification of the pinned cage. The outside diameter of one ring was machined to provide ten .125 inch deep slots at a 45° angle to the bearing bore. The intent of this design was to provide an air flow through the bearing to carry out wear debris. This ring is shown in Figure 11.

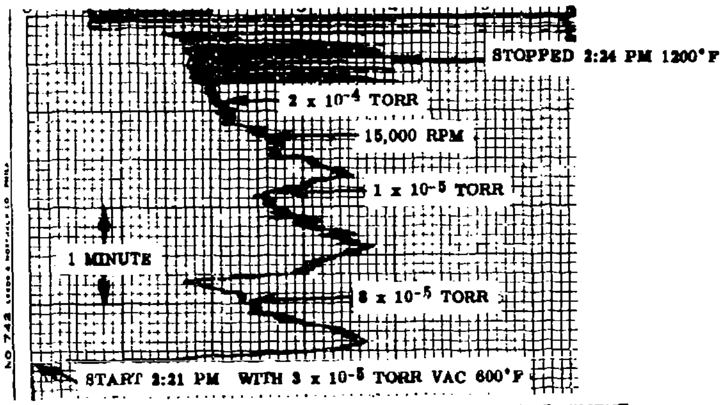
The third roller bearing configuration evaluated was a full complement roller design. See Figure 11.

Test R-1 was conducted at room temperature in air with a 75 pound radial and a 25 pound thrust load. The test was terminated after 15 seconds of operation. The friction had increased from less than 0.1 to a value in excess of .2. A speed of 6000 rpm was attained. Examination of the bearing after test indicated severe scoring of roller ends and the race thrust faces.

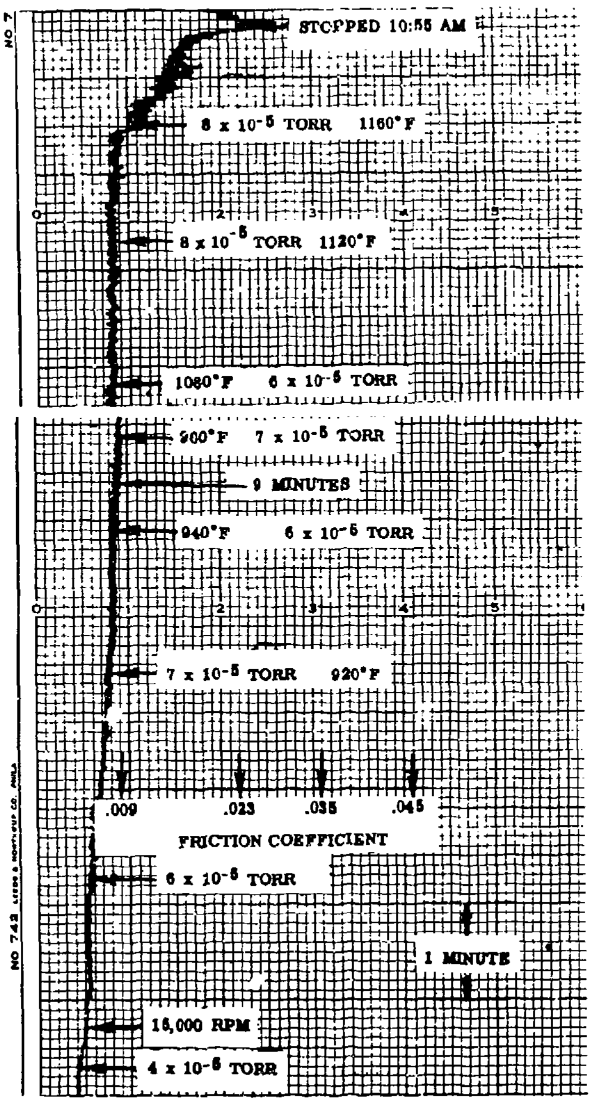
TABLE 11

ROLLER BEARING TEST SUMMARY

TEST NO.	BEARING MATERIAL	LUBRICANT	TEMP. °F START	TEMP. °F MAX.	RPM MAX. SPEED	INITIAL PLAY INCHES	FRICTION START	FRICTION RUN	LIFE MIN.	RADIAL PLAY INCREASE INCHES/HOUR	REMARKS
R-1	TiC	None	650	800	8,000	.0004	0.15	.08	2	------------	Erratic friction and seizure.
R-2	TiC	None	70	----	6,000	.0004	.008	.004	15 sec.	------------	Seizure caused by differential heating.
R-3	TiC	Phthalocyanine	900	1350	15,000	.0004	.23	.15	29 sec.	.0393	Excessive wear.
R-4	TiC	Phthalocyanine	900	1200	15,000		.003	.01	11	.0475	Slotted cage, stopped due to wear.
R-5	TiC	M-1284	900	1250	15,000		.033	.038	30	.0232	Excessive wear.
R-6	TiC	None	900	970	12,000	.0009	.029	.026	7-1/2	.0383	Excessive wear.
R-7	TiC	B11	900	1180	15,000		.002	.035	10	.036	Excessive wear
R-8	TiC	PbO	900	1150	15,000		.013	.016	55	.0205	Excessive wear
R-9	TiC	Collodial Graphite	900	1210	15,000		.004	.013	40	.00015	Full complement. ATJ graphite spacer rollers.
R-10	TiC	None	900	910	15,000	.0009	.004	.012	12	.0345	Radial load only
R-11	TiC	None	900	1120	15,000	.0009	.043	.018	60	.011	Full complement. Stopped for Inspection
R-12	TiC	PbO	900	1020			.031		1	------------	PbO on races only. Full complement.
R-13	TiC	PbO	420	1230	15,000		.078	.023	1 hour 52 min.	.0237	PbO on races and rollers. Full complement.
R-14	TiC	Colloidal Graphite	900	1090	15,000		.009	.010	40	.00015	Full complement. ATJ graphite spacer rollers.
R-15	TiC	Colloidal Graphite	900	1070	15,000		.039	.025	27	.0226	Full complement. SiC graphite spacer rollers.
R-16	TiC	B11	900	1220	15,000		.028	.024	45	.0378	.002" lube coating on TiC spacer rollers.
R-17	TiC	Phthalocyanine Chromic Acid Pretreat	900	1280	15,000		.007	.020	60	.0130	Full complement.
R-18	TiC	Colloidal Graphite	1500	1520	15,000	.002	.040	.020	30	.0008	Full complement. graphite 2480 spacer rollers. Final temperature 920°F.
R-19	TiC	Colloidal Graphite	900	1060	14,000		.002	.015	4	------------	Full complement. 50% Ni 50% MoS_2 spacer roller.
R-20	TiC	Colloidal Graphite	600	1200	15,000	.002	.035	.030	3-1/2	.0257	Full complement. ATJ graphite spacer rollers in vacuum at 2×10^{-5} mm Hg



TEST R-20 ROLLER BEARING (NO CAGE) FULL ROLLER COMPLEMENT
ATJ GRAPHITE SPACER ROLLERS .002 RADIAL PLAY



TEST B-21 BALL BEARING (NO CAGE) 900°F IN VACUUM
75# RADIAL LOAD, 25# AXIAL LOAD

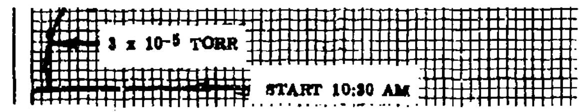


FIGURE 9 FRICTION CURVES BALL AND ROLLER BEARINGS IN VACUUM

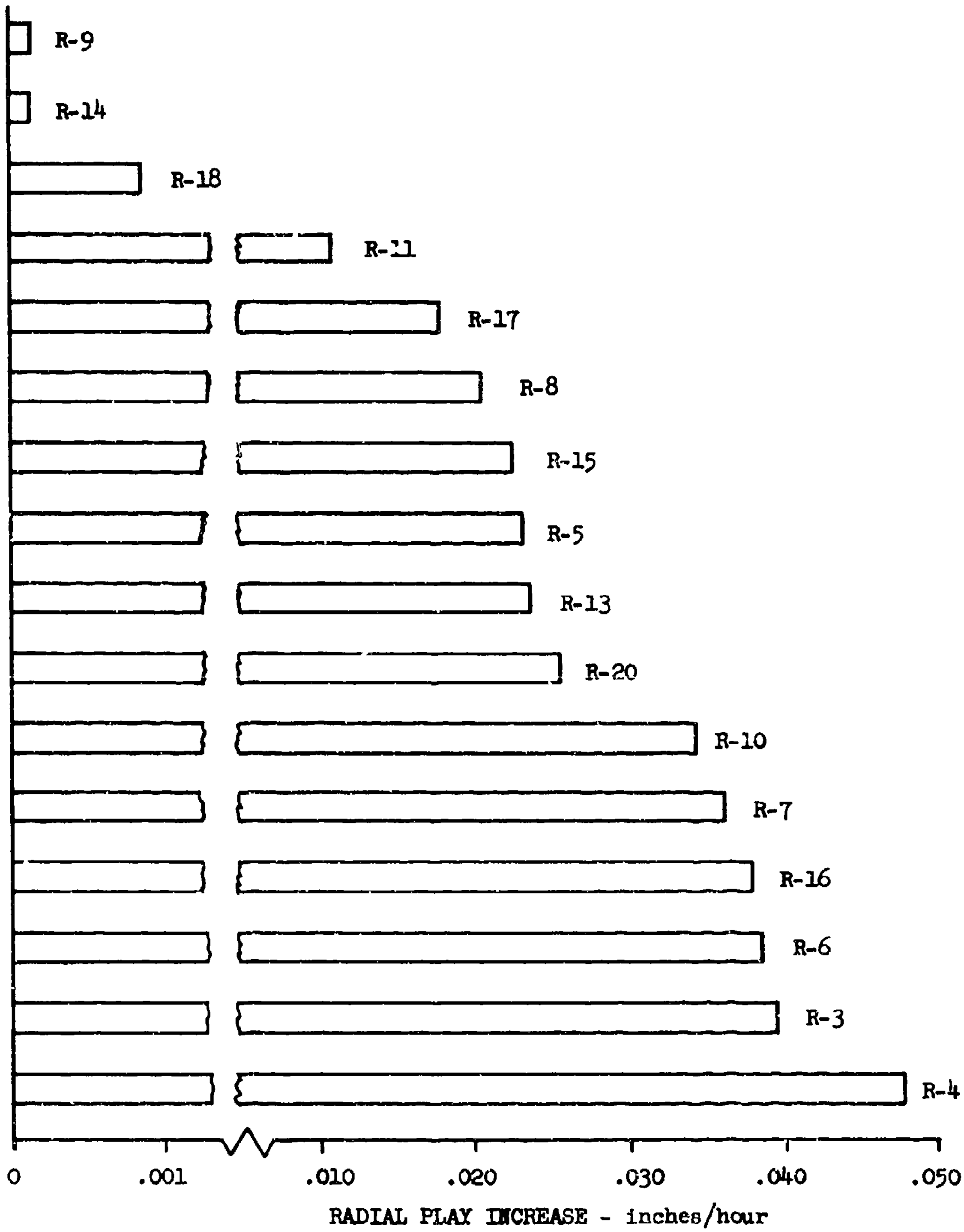
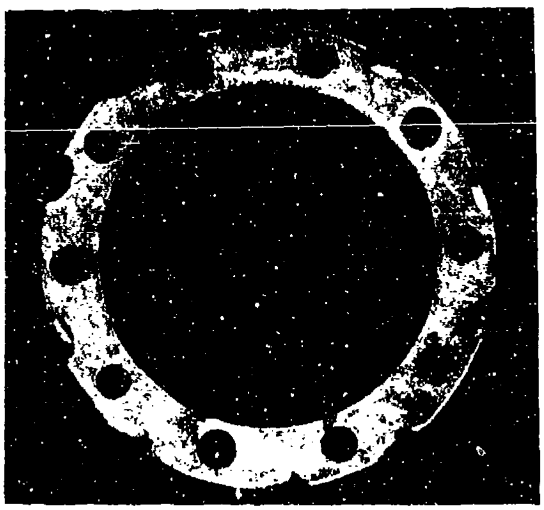


FIGURE 10 ROLLER BEARING TEST - WEAR RATES

BALL BEARING AFTER 1500°F OPERATION IN AIR, TEST B-18

RACEWAYS OF 1500°F BALL BEARING TEST B-18



SLOTTED CAGE RING FOR ROLLER BEARING TEST R-4

FULL COMPLEMENT ROLLER BEARING AFTER TEST R-14

FIGURE 11 TESTED BALL AND ROLLER BEARINGS AND COMPONENTS

A photograph showing a magnification of a scored roller is shown in Figure 12. Examination of the rollers under magnification indicated that the radius provided did not smoothly blend with the roller ends. This radius was considered to be the cause of the scoring and subsequent high friction values. Prior to assembly of the bearing for test R-2, the "chamfer" on all roller ends was radiused from .005 to .010 inches.

Test R-2 was planned for operation at 900°F in air with a 75 pound radial and a 25 pound axial load. In the initial test setup a heater unit was used on one side of the bearing only. With this arrangement the outer race heating temperature on the heater side reached 1000°F. The opposite side of the outer race indicated 800°F. Upon initiation of shaft rotation the test bearing seized after about 2 to 3 seconds of operation.

In examining the bearing after test all rollers were found to be in a skewed condition. The raceways indicated end loading of the rollers during the heating cycle. The end loading was evident only on the low temperature side of the bearing. All exposed surfaces of the rollers, the raceways and cage were coated with a dark shiny purple oxide film. These surfaces appeared to be in good condition.

The failure in this test was attributed to the axial thermal gradient across the raceways which caused the roller end loading with subsequent skewing and seizure. This failure illustrates the sensitivity of the roller design to axial thermal gradients.

Because the bearing remained in good condition, it was reinstalled in the test machine for continuation of test R-2. A new heating unit had been fabricated to provide radiation to both sides of the bearing.

After a gradual heating period for 1 hour the bearing attained temperatures of 675°F on the front and 625°F on the rear. Inasmuch as frictional heating was expected to provide a temperature increase, rotation was initiated. The initial breakaway friction value was 0.15. The friction then decreased for about 30 seconds to .08. After 30 seconds of operation the friction became erratic with a seizure occurring after a total time of 2 minutes. A maximum speed of 8000 rpm was attained. The final bearing temperature was 970°F front and 860°F rear.

Examination of the R-2 test bearing after test revealed an unusual condition. The 0.5% Ti Mo main cage ring was heavily oxidized. The oxidation products had deposited or reacted with all exposed bearing surfaces. This deposition or reaction is evident on the bearing outer race shown in Figure 13. The bearing press fit installation in the housing apparently protected the center section of the ring from the deposition or reaction products.

The examination of the roller ends and race thrust faces revealed a bright polished surface. The raceways and rollers appearance indicated that

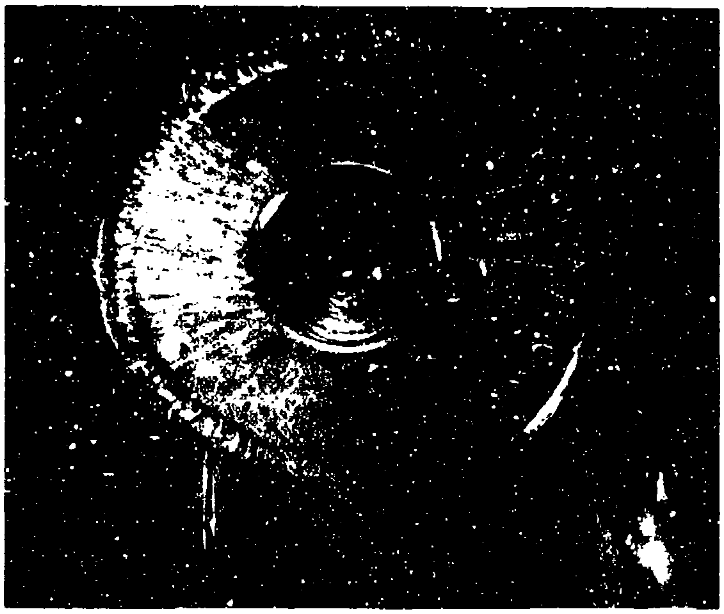


FIGURE 12 ROLLER END WEAR MAGNIFIED

FIGURE 13 ROLLER BEARING TEST R-2

about half the width of the race was carrying the load. The load zones were worn rough and pitted. It is considered that the deposition or reaction products from the 0.5% TiMo cage contributed to the wear and deterioration of the raceways and rollers. These products were apparently thrown out of the bearing on the thrust faces. In the raceway, however, the products were retained and were abrasive in nature.

For subsequent in-air tests, the 0.5% TiMo alloy main rings were coated with an oxidation protective surface. This surface was a Boeing developed silicide coating, DiSil-1, which had demonstrated effective oxidation protection on Mo alloys at 2000°F for over 40 hours. This coating was intended to eliminate any influence of the Mo alloy oxidation products on roller bearing performance.

During the protective coating application the 0.5% Ti-Mo alloy rings were exposed to a temperature of 1850°F. This high temperature exposure caused an out of round distortion of 0.005 to 0.007 inch in the main rings. This factor eliminated the possibility of using the DiSil-1 coating for the cage main rings.

In tests R-3, R-5, R-7 and R-8 the base line configuration, the pinned cage, was evaluated with different dry films. The lead oxide coated bearing test R-8 indicated the lowest wear rate in these tests. (Figure 10) A significant variation in the relative wear of rollers, inner race and outer race was evident in these tests. One cause for this variation may be due to roller installation misalignment which may be inherent in the pinned cage design. This factor may also contribute to the increased total wear evident in all the caged bearing designs.

Tests R-4 and R-6 were conducted to determine the effect of wear debris removal during tests with the slotted cage. With the exception of the slotted cage modification, tests R-6 and R-4 were identical to tests R-1 and R-3 respectively. Examination of the bearings and housing after tests R-4 and R-6 showed significantly less debris in the bearing and significantly more debris in the housing than in previous tests. The slotted cage was apparently effective in creating sufficient air flow through the bearing to remove wear debris. The beneficial effect of wear debris removal was evident from the increased run time of test R-6 over test R-1. The removal of wear debris decreased the tendency toward bearing seizure. In comparison of test R-3 with R-4 (the slotted cage) an increased wear rate was shown for R-4. This may be due to the lubrication effect of the debris. A possibility exists, therefore, that the rate of debris removal is an important factor.

The third roller configuration tested (R-11), the full roller complement bearing, exhibited a lower wear rate than all previous roller tests. (Figure 10) This may be the result of decreased stress due to the increased roller complement. A constant bearing friction value of .018 was recorded during this test. The performance of this bearing is significant in light of the fact that the bearing was unlubricated.

Test R-10 was conducted to determine the effect of axial load on roller bearing wear. In this test, the minimum axial load (less than 1 pound) required to retain the bearing on the test shaft was used. The full 75 pound radial load was applied. The wear rate under this condition was .025 inch per hour. Examination of the bearing after test indicated that a significant temperature differential occurred across the bearing inner race. It is considered that this factor would have caused roller skewing. The skewed rollers then may have caused the excessive wear rate. Apparently the elimination of axial load increased the bearing sensitivity to roller skewing with the resultant high wear.

In test R-12 a full complement carbide bearing was tested with races coated with the lead oxide film. After one minute of operation the bearing seized. Throughout the one minute run several high torque peaks were indicated. Examination of the bearing after test showed the rollers to be in a skewed condition. Light scoring was evident on the roller ends.

In test R-13 the full roller complement bearing was again evaluated with the lead oxide film coating. In addition to applying lead oxide to the raceways, all rollers were also coated. The bearing test was terminated due to an excessive wear condition after one hour and 52 minutes.

Test R-9 was originally scheduled for evaluation as a pinned cage design with a raceway and roller lubricant film of calcium fluoride. A chemical reaction occurred between the calcium fluoride and the titanium carbide cermet material. No bond could be obtained between the fluoride and the carbide materials.

Because of the difficulties encountered with the fluoride film application, another bearing was substituted for the R-9 test. The substituted bearing was the final basic design modification evaluated in the Phase I roller bearing tests. It consisted of a full roller complement design in which alternate spacer rollers were fabricated from a lubricant material. The material selected for the initial lubricant spacer roller was ATJ graphite. Prior to test the assembled bearing was dipped into a colloidal suspension of graphite to apply an initial coating of dry film lubricant to all surfaces. Because the bearing design was not originally intended for a full complement bearing, a very high (0.350 inch) circumferential clearance resulted. The bearing was operated for a period of 40 minutes. During the final minute of operation the friction increased to a peak value of .045. Examination of the rollers and raceways revealed a light (.0001 inch) build-up of graphite on all surfaces. The lubricating rollers had decreased in diameter 0.003 inch. One lubricating roller showed severe end wear. Both ends of this roller were chamfered about 1/16 x 45°. It is considered that this chamfered condition was caused by roller skewing as a result of the high circumferential clearance in the bearing. Wear measurements of the carbide surfaces showed that this test resulted in the lowest wear rate (0.00015 inch/hour) of all bearings tested in the Phase I program. (Figure 10)

Test R-14 was a repeat of the R-9 test cited above with the exception of a change in lubricating spacer roller length. In order to reduce the spacer roller end wear the length was reduced to 0.001 inch less than the carbide rollers. This bearing operated for the identical time period as test R-9. The wear rate and type failure were also identical.

The decrease in lubricating spacer roller length produced no significant effect on bearing performance. A frictional torque vs. time chart for this test is shown in Figure 8.

In test R-15 a silicon carbide-graphite composite was evaluated as a spacer roller material. The test was terminated due to high friction after 27 minutes of operation. Again end chamfering was noted on one roller. The wear rate (see Figure 10) was significantly higher with this composite than with the ATJ graphite material.

In test R-16, 0.005 inch undersize carbide rollers were coated with a 0.002 inch thickness of 811 dry film. Five of these rollers were used as spacer rollers in the test bearing. The test was terminated after 45 minutes due to an excessive wear rate. Examination after test revealed that the 0.002 inch thickness of dry film was completely removed from the spacer roller diameter.

Test R-17 was a full complement roller bearing with races and rollers coated with a phthalocyanine film. The chromic acid pretreatment, described in the "Materials Section" of this report, was used prior to film application. The wear rate for this test (see Figure 10) was higher than the unlubricated full complement bearing test number R-11.

In test R-18, a No. 2480 oxidation resistant graphite material was used as a lubricating spacer roller. The inner race was reduced in diameter to provide a .002 inch radial play. After 30 minutes of operation, the test was terminated due to a seizure condition. Examination showed that one roller was chamfered on both ends. It had skewed 90° and caused the seizure condition. Wear rate on this bearing, 0.0008 in 1 hour, was the second lowest of all roller bearings tested.

In test R-19, a lubricating spacer roller consisting of a 50% nickel, 50% molybdenum disulfide hot pressed composite was evaluated. After 4 minutes of operation, the test was terminated due to seizure. Examination revealed a cracked outer raceway which was caused by high stress resulting from a large (in excess of .001 inch) build up of nickel on the raceways.

The final Phase I roller bearing test, R-20, was conducted under vacuum conditions. The bearing selected was the previously tested low wear rate ATJ graphite spacer roller design. The inner race was reduced in diameter to provide a radial play of 0.002 inch. It was recognized that the effectiveness of graphite lubrication was reduced under vacuum conditions.

However, it was considered that the effectiveness of graphite lubrication in this bearing design should be investigated. After 3-1/2 minutes of operation under pressures between 2 x 10^{-4} and 2 x 10^{-5}mm Hg, the bearing seized. Subsequent examination revealed a 90° skewed roller condition and lubricating roller chamfer similar to test R-18. A 170 times increase in wear rate over the in-air test (R-14) was measured. A coefficient of friction versus time recording for the test is shown in Figure 9.

4. DISCUSSION AND ANALYSIS

This section includes a general analysis of the three types of bearings evaluated in the Phase I program.

Plain Bearings

All plain bearings tested exhibited high wear rates and high friction when compared to the rolling element bearings. None of the bonded dry films tested were satisfactory as lubricants under the operating conditions investigated. However the dry film coatings did, to a small degree, prevent initial seizure in this type of bearing. The friction data, in general, indicates that the dry film lubricant coatings exhibited higher friction during start than during the high speed run. This may be attributed to the general decrease in friction coefficient of refractory materials with increases in temperatures.

The effectiveness of the phthalocyanine film as a lubricant is directly related to the bearing material. This factor is very evident from the comparison of the wear rates in Figure 3. The refractory hard materials exhibited low wear rates (less than .002 inch/hour) whereas the relatively soft superalloy wear rates were in excess of .020 inch/hour.

The high temperatures introduced by the sliding friction inherent in the plain bearing design creates additional operational problems. Localized heating at the sliding interface introduced high thermal stresses and subsequent fracture in the majority of the refractory materials tested: The high temperatures also necessitate obtaining dry film lubricants which are effective over a broader temperature spectrum.

Ball Bearings

Three basic configurations were tested in the ball bearing effort. It was demonstrated in each type that bonded dry film lubrication is inadequate to cope with the conditions imposed. None of the dry lubricants resulted in a significant performance increase over the unlubricated bearings.

The full complement bearing was the most satisfactory of the designs tested. The success of this design in the high temperature environment is attributed to the material. The temperatures produced by frictional heating in a full complement design are of several hundred degrees in magnitude. Conventional steel bearings are therefore speed limited due to frictional heating and the subsequent softening of the material. However, the full complement bearing made from the carbide material was not adversely influenced by the frictional heating. This material selection therefore resulted in a moderately successful full-type bearing. The original selection of wide curvatures was also a contributing factor to the success of this type bearing. It was apparent from the 1500°F test that the oxidation product of the carbide material at this temperature functions quite adequately as a lubricant. This test exhibited a very low wear rate and the bearing was definitely capable of further operation when stopped. The source of this lubricant and hence the performance of the bearing was impaired in the vacuum environment.

Roller Bearings

The investigation of the various methods of roller separation indicated the most significant effect on roller bearing performance.

The original design which utilized the pinned cage was the least satisfactory. All bearings with pinned cages exhibited high wear rates. This may have resulted from roller misalignment in the cage. The design did eliminate the high speed sliding friction generally associated with conventional designs. The surface speed was reduced from a conventional cage value of 3100 feet per minute to less than 300 feet per minute. Unlike conventional high speed, high temperature bearing failures, no cage failures were obtained with this design. The maximum pin wear did not exceed 0.002 inches in any test. This cage design may prove to be satisfactory for high temperature applications which have other than a bonded dry film lubrication system.

The low wear rates of the lubricant spacer roller full complement design indicated a high potential for this separator concept. The primary reason for the success of this concept is believed to be the increased quantity of dry lubricant available in the bearing. In comparison to the bonded film bearings, the lubricating spacer roller introduced several thousand times the quantity of dry lubricant.

The failures in this design were typified by the skewed condition of the lubricating spacer roller. It is considered that the primary cause for these failures was the high, 0.350 inch, circumferential clearance in the bearing. A reduction in the circumferential clearance to 0.050 inches was therefore planned for the Phase II design. It was believed that this modification would reduce the roller skewing tendency and provide an improved balanced design.

D. PHASE I CONCLUSIONS

1. None of the conventionally bonded dry films tested were satisfactory as lubricants for the bearings under the operating conditions investigated.

2. Plain bearings exhibited higher friction coefficients and wear rates than the ball and roller bearing designs investigated.

3. The best plain bearing performance was obtained with a titanium carbide bearing and shaft both coated with a phthalocyanine film. It operated within a friction coefficient range of 0.28 to 0.22 and had a wear rate of .001 inches per hour.

4. Two different bearing designs, which used unconventional dry film lubricant techniques, demonstrated the feasibility of operation at 15,000 rpm in 900°F air.

   One feasible design, a full complement titanium carbide cermet roller bearing which used ATJ graphite as a spacer roller to provide a replenishing supply of lubricant film, had the lowest wear rate (0.00015 inches per hour).

   The other feasible design, a full complement titanium carbide cermet ball bearing which was lubricated by the oxide film formed on the bearing surfaces at elevated temperature, had the lowest friction coefficient ($\mu = 0.002$) of all bearings tested in Phase I.

PHASE II BEARING TESTS TO 1500°F IN VACUUM

The following contractual requirements were originally specified for the Phase II program:

1. To develop dry lubrication techniques and conduct research on new dry film formulations.

2. To test one hundred bearings at temperatures to 1500°F at 15,000 rpm in air and vacuum environments.

3. To expose ten bearings to nuclear radiation prior to test.

After completion of Phase I, the program was directed toward accomplishing the above requirements. A lubricant development program which was initiated at the beginning of the contract was continued. This lubricant development program was supplemented by a subcontract with the Washington State University. New designs for ball and roller bearings which used a lubricant composite material as a rolling element separator were completed. Procurement and testing were initiated. The design and fabrication of a container for radiation exposure were completed.

In the initial seven bearing tests conducted, failures of the lubricant composite materials indicated that an increased emphasis on lubricant development in the program would be desirable. As a result, the contract was amended to include the following supplemental agreement:

> "The Contractor shall fabricate and evaluate by means of compressive load fracture tests lubricant compacts made of 500 different combinations of materials. The best fifty material combinations made into lubricant compacts shall be further evaluated by laboratory wear tests and by use in the fifty bearings to be tested.......".

Under the amended program the lubricant composite materials were fabricated and tested. Six additional roller bearing tests were conducted with the new composite materials in a vacuum environment. These tests all resulted in early failures due in part to excessive lubricant build-up within the bearing. During the same time period an investigation of a graphite separator bearing design was conducted under a Boeing Company sponsored research program. These tests showed a significant improvement in performance for the graphite separator cage over the graphite rolling element separator design.

Upon completion of the aforementioned tests, the results of the program were reviewed by the Aeronautical Systems Division Project Monitor. During this review the results of the testing completed were analyzed with respect to the continuation of the contract effort. It appeared desirable to modify the bearing design and to incorporate a lubricant composite material separator prior to continuation of bearing testing. The program was therefore redirected to include the following changes:

1. Modify all remaining roller bearing rings to incorporate a raceway relief radius.

2. Fabricate separator rings and pins for both ball and roller bearings.

3. Using best lubricant compacts developed, test bearings to prove the new design.

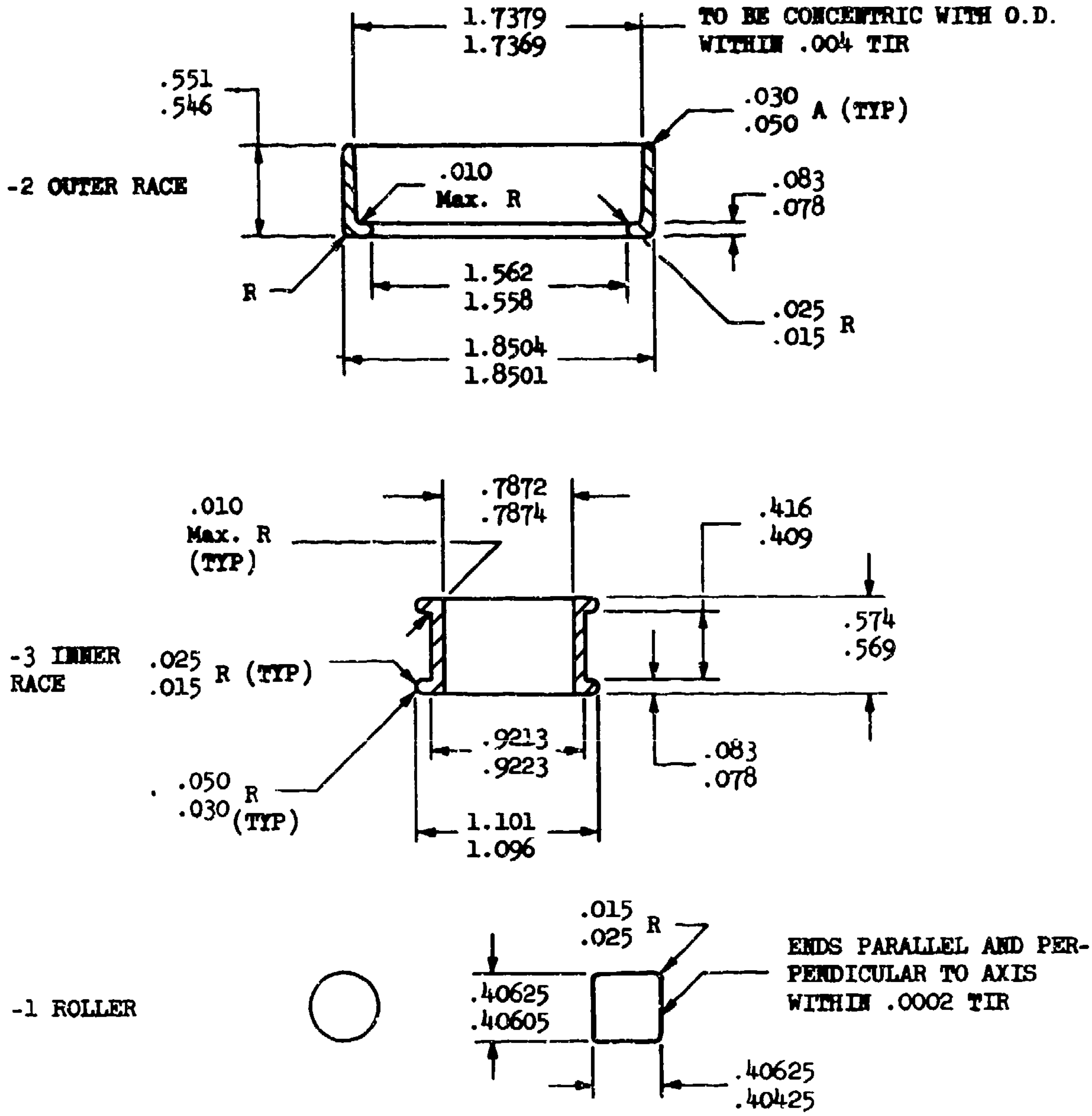
The bearing modification and separator component fabrication cited above were completed. Five additional bearing tests were conducted in the high temperature-high vacuum environment. These tests indicated the feasibility of the lubricant composite separator design for high vacuum operation. Details of the work completed are included in the following sections of this report:

A. BEARING DESIGN

The design of the bearings used for the Phase II program was predicated upon the results of the Phase I testing. (Phase I tests are summarized in Tables I, II & III of this report). The Phase I tests indicated that the rolling element bearings were superior to the plain bearing design under the test conditions specified by the contract.

1. ROLLER BEARINGS

The lowest wear rates in the Phase I program were obtained with a full complement roller bearing. It was a double lip inner and a single lip outer race design. The bearing raceways were fabricated from a titanium carbide cermet, K162-B. The bearing had a roller complement of ten. Five load carrying rollers of titanium carbide were separated by five ATJ graphite-lubricant spacer-rollers. The bearing was originally designed for operation with five 3/8-inch diameter carbide rollers and a roller-controlled separator. When used as a full complement design, the circumferential clearance was 0.300 inch. The maximum radial play was 0.001 inch.



5 PARTS REQUIRED PER ASSEMBLY - LENGTHS OF ALL PARTS IN ONE ASSEMBLY TO BE WITHIN .0002".

1. Inner race to be concentric with bore within $\pm.0003$ TIR.
2. Raceway taper not to exceed .0002 over length of raceway.
3. Material is Kennametal K162B Titanium Carbide.
4. Thrust faces to be $\perp$ to bearing ℄ . Runout parallel to ℄ not to exceed .003 TIR.

FIGURE 14 PHASE II ROLLER BEARING

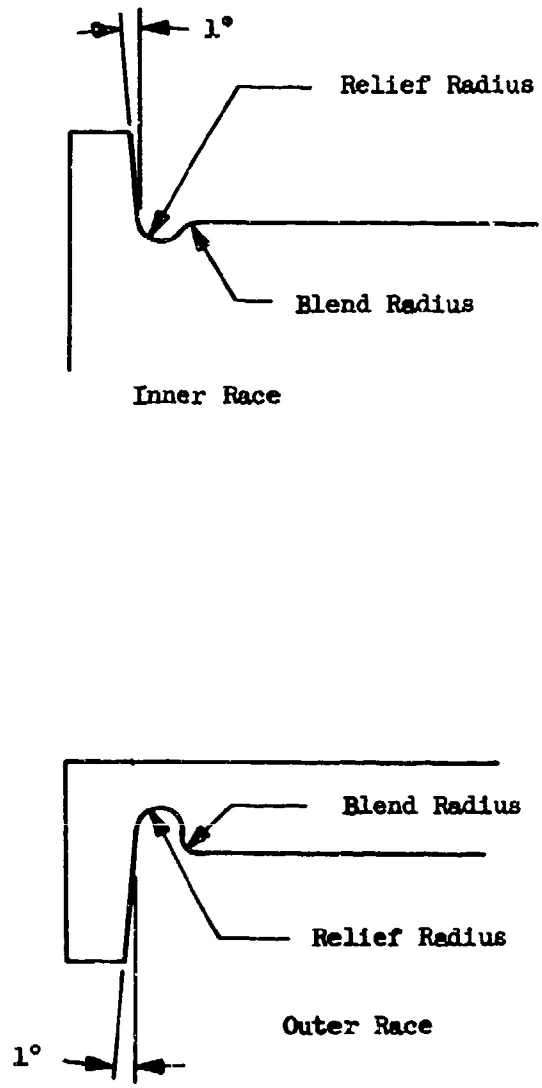


FIGURE 15 ROLLER BEARING RACEWAY MODIFICATION

In the original Phase II program a series of different lubricant composites were planned for evaluation as spacer-rollers in a similar bearing design. The detail drawing of the design selected is shown on Figure 14. In this design the circumferential clearance was reduced to 0.050 inch by incorporating a larger diameter roller on the same pitch circle as the Phase I bearing design. The roller size was increased to 0.40625 inch. In order to accommodate the dry film lubricant build-up on the raceways and load-carrying rollers, the radial play was increased to the range 0.0021 to 0.0041 inches.

Under the redirected Phase II program, the roller bearing design was modified to provide a raceway relief to permit egress of wear debri. Also incorporated in this raceway modification was an effective decrease in thrust face shoulder height. (See Figure 15) These changes were indicated as a result of the analysis of the failed bearings tested in the initial Phase II program. (This analysis is covered in detail in section "C" of this report).

The major modification of the bearing design under the redirected program was the incorporation of a lubricant composite material into a roller separator. To facilitate manufacture the number of rollers was increased from the original 5 to 6. The assembly and the various components of the separator are shown on Figure 16.

The cage was controlled by permitting the lubricant composite material to ride on the inner race. The design clearance between the inner race and the lubricant composite material of the separator was 0.005 inches. The roller pocket clearance was 0.010 inch.

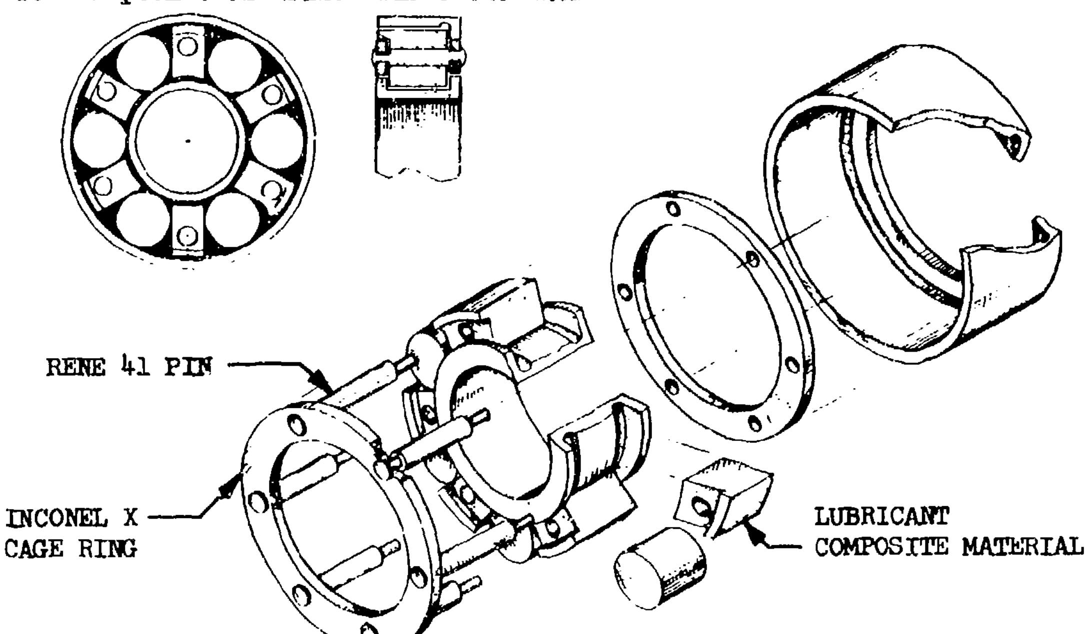
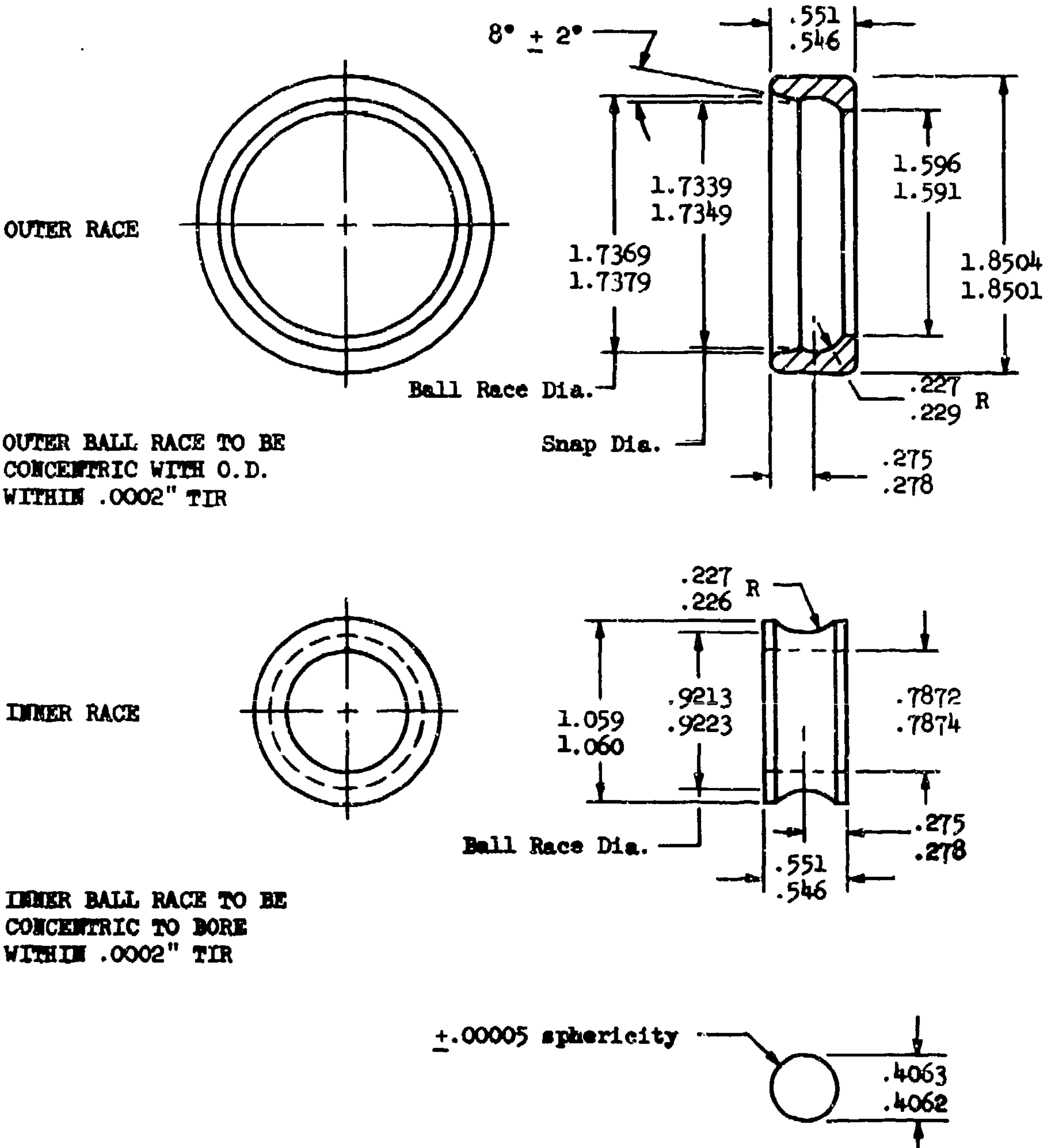


FIGURE 16 ROLLER BEARING LUBRICANT COMPOSITE SEPARATOR



1. Ball race surface finish not to exceed 5 RMS.

2. Ball race to be parallel to face within ±.0002 TIR

3. Material is titanium carbide K162B.

FIGURE 17 PHASE II BALL BEARING

2. BALL BEARING

The original ball bearing design followed the concept cited above. It was an angular contact type with five carbide load-carrying balls and five lubricant-composite spacer balls. The raceway curvatures were maintained at 56% to decrease ball-to-race sliding and to permit egress of wear debris. A detail drawing of this design is shown on Figure 17.

Under the redirected Phase II program the ball bearing design was modified to incorporate six carbide load-carrying balls and a lubricant composite separator. The separator was controlled by contact of the lubricant composite material on the inner race lands. The design clearances were 0.005 inch between the lubricant composite material and the inner race land and 0.010 inch in the ball pocket. A sketch of this separator concept is shown on Figure 18.

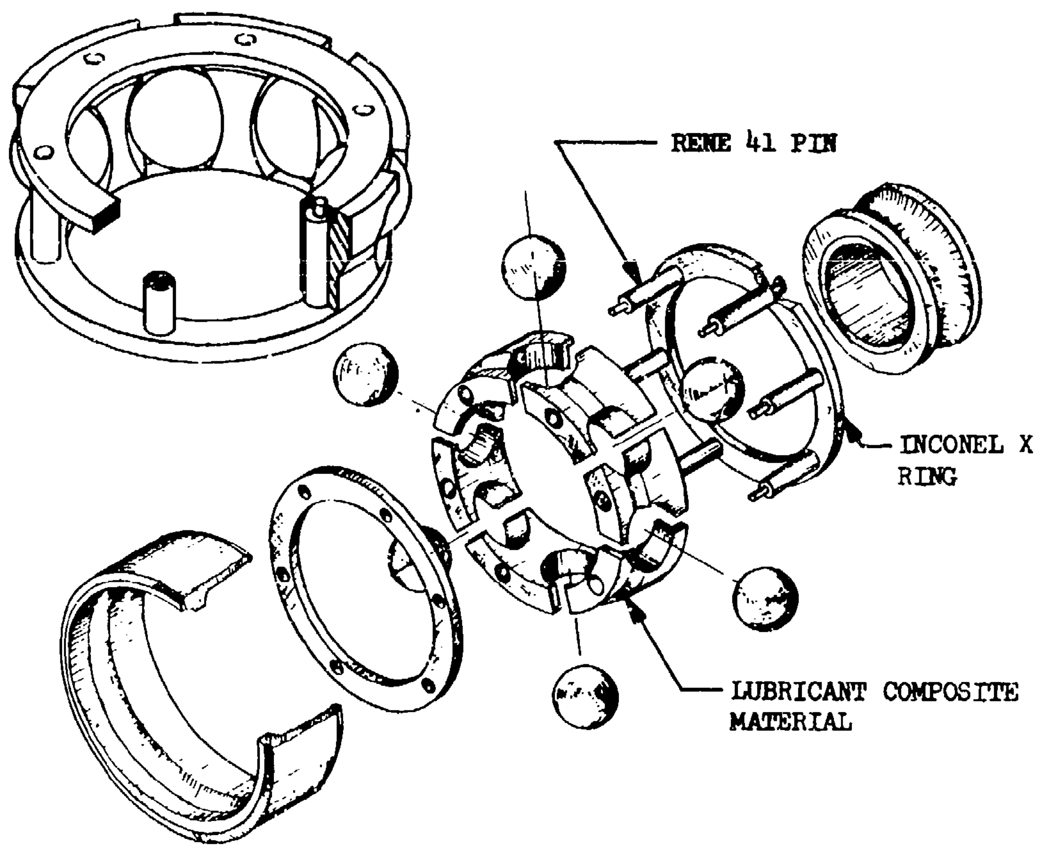


FIGURE 18 BALL BEARING LUBRICANT COMPOSITE SEPARATOR

B. TEST EQUIPMENT FOR 1500°F AND 10^{-6}mm Hg

The test equipment used for the Phase I program was modified for the Phase II program. The following discussion of the design includes changes incorporated for the Phase II program.

1. DRIVE AND LOAD SYSTEMS

The drive and load systems used in the Phase I test equipment were not changed for the Phase II program.

2. FRICTION MEASUREMENT

The friction measuring system was modified to eliminate effects of elevated temperature and vacuum on the strain gage instrumentation. A ceramic adhesive was used to bond a new platinum alloy strain gage elements to the strain beams. This system, which was cured at 1000°F, provided an accurate (within $\pm$ 1%) friction recording for all tests conducted in the redirected Phase II program.

3. HEATING SYSTEM

In Phase I bearing temperatures of 900°F and 1500°F in air were obtained with a nichrome wire resistance heater located on each side of the test bearing. A single heater was used for plain bearing tests. With two heating elements, the temperature gradient across the outer race of anti-friction bearings did not exceed 15°F.

Tantalum wire of the same diameter as the nichrome was used satisfactorily for Phase II tests in vacuum at 1500°F.

4. VACUUM SYSTEM

The vacuum system originally consisted of a mechanical pump and a 4-inch diffusion pump connected to a cold trap. This system would provide pressures as low as 1 x 10^{-6}mm of Hg. With neoprene lip seals installed and the shaft rotating at 15,000 rpm, a vacuum of 5 x 10^{-5} was held over a period of one hour. Viton A and Teflon seals provided the same pressure performance, but with less seal wear.

During the final Phase I tests, a spring-loaded graphite face seal with the inner race of the bearing as a sealing face was used for testing a ball and a roller bearing in vacuum. The pressure increased to 50 microns on the first test due to poor lubrication of the seal, but a vacuum of 2 times 10^{-5} was attained on the second test using an increased supply of 702 fluid as a lubricant.

For the Phase II program, a magnetic graphite face seal was ordered and installed on a new test spindle. The new assembly consisting of a brass sleeve adapter, magnetic graphite-face seal and test spindle performed satisfactorily at 15,000 rpm, 1500°F and a pressure of 2×10^{-5}mm Hg. During the initial Phase II tests, slight leakage occurred at the lead-in wires for the heater elements and the strain bars. An application of red glyptal to the lead-in wire sealing glands alleviated this problem.

Prior to conducting tests under the redirected Phase II program, two modifications to the vacuum system were investigated to determine if a harder vacuum could be obtained. The initial modification consisted of providing a low pressure, 1×10^{-3}mm Hg, on the side of the shaft seal opposite the test chamber. This pumping which was accomplished with a mechanical roughing pump did not result in obtaining a lower pressure.

The second modification consisted of providing an increased pumping capacity. The original pumping system was replaced with a CVC (DK45A) oil sealed, two stage rotary roughing pump and a CVC (BMC721) six inch diffusion pump.

With this increased pumping capacity a minimum pressure of 7×10^{-6}mm Hg was obtained with shaft rotation at 15,000 rpm.

C. BEARING TEST RESULTS AND ANALYSIS

The bearing tests in the original Phase II program were planned to determine the feasibility of operation at 15,000 rpm in air and vacuum throughout a temperature spectrum from 250°F to 1500°F. During the final tests in Phase I, it was determined that operation in a vacuum was significantly more detrimental to bearing performance than operation in air. For this reason the initial testing in Phase II was planned as screening tests in a vacuum.

Because of the successful performance of the lubricant spacer-roller in the Phase I program, and because of simplicity in fabrication, the bearing design selected for initial Phase II testing was the lubricant-composite spacer-roller bearing. A final comparison of the roller and ball bearing designs was planned after the optimum lubricant composite material was selected in the roller bearing tests.

The initial tests were conducted at 15,000 rpm with a 75-pound radial and a 25-pound axial load. The results of these tests are included in Table VI as tests No. 1 through No. 7. The three preliminary tests conducted in Phase I in a vacuum environment are also tabulated.

The bearing failures in tests No. 1 through No. 7 were attributed to the dimensional instability with temperature of the lubricant composite materials. The successive tests, No. 8 through No. 13, were conducted with stabilized lubricant composite materials. Details of the thermal expansion measurements

TABLE IV

PHASE II-HIGH VACUUM BEARING TESTS

Test No.	Lubricant-Composite	Vacuum mm Hg	Temperature °F start	Temperature °F max.	Max RPM	Friction start	Friction run	Radial Play - Inches before test	Radial Play - Inches after test	Life in Minutes	Remarks
B-20*	K-162B Oxidized	4×10^{-5}	800	1080	15,000	.002		.002		34	Gradual friction increase; raceway pitting.
B-21*	K-162B Oxidized	2×10^{-5}	900	1230	15,000	.019	.008			25	Gradual friction increase; raceway pitting.
B-20**	ATJ Graphite	2×10^{-5}	600	1200	15,000	.035	.030	.002		3.5	Excessive wear of graphite roller ends; ineffective lubrication.
1	No. 18	8×10^{-5}	1470	1620	11,000	.062	.041	.0028	.0104	1.5	Lubricant composite disintegrated .005 in. roller wear; .0022 build-up on I.R.
2	No. 28	5×10^{-4}	1475	1800+	12,000	.015		.0030	Zero	3.75	Lubricant build-up resulted in .0037 in. internal interference; excessive friction.
3	No. 99	1.5×10^{-5}	600	800		.049	.036	.0032		2.5	Lubricant composite disintegrated.
4	No. 22							.0028			Outer race fractured during installation.
5	No. 23	1.6×10^{-5}	150		5,500	.020		.0025		1.2	Lubricant composite disintegrated.
6	No. 99	2.5×10^{-5}	900	1350	6,000	.046	.040	.0027	.0036	.75	Lubricant composite disintegrated.
7	No. 45	2.8×10^{-5}	70	700	15,000	.035	.024	.0026	.0052	5.7	Lubricant composite disintegrated.
8	No. 203	2.5×10^{-5}	1500	1550	8000	.044	pegged	0.00225	0.00069	0.2	Carbide rollers and inner race thrust face scoring; lubricant build-up; excessive friction.
9	No. 209	2.0×10^{-5}	1500	1500	----	----		0.0023	----	0	Lubricant-composite fractured during initial shaft rotation.
10	No. 220	1×10^{-4}	1400	1450	4000	.025	.046	0.00150	0.00357	0.8	Carbide rollers and inner race thrust face scoring; high wear rate; inadequate lubrication.
11***	No. 263	5×10^{-6}	70	----	8000	.007	.044	0.0033	0.00165	1.5	One lubricant composite fractured; lubricant build-up; very light scoring of carbide roller ends and inner race thrust face.
12	No. 144	1.5×10^{-5}	1500	1800+	10,000	.068	.020	0.0018	Zero	1.2	Lubricant build-up resulted in 0.0026 inches internal interference; excessive friction.
13	No. 262	3×10^{-5}	1500	1800+	7000	.040	.050	0.0019+	Zero	0.6	Lubricant build-up resulted in 0.0010 inches internal interference; excessive friction.

*K-162B Titanium carbide full complement ball bearings tested during Phase 1.

**K-162B Titanium carbide roller bearings tested during Phase 1.

***Test 11 was conducted with a 27 - 1/2 pound radial and 2 pound thrust load; all other tests had a 75 pound radial and 25 pound thrust load.

NOTE All tests conducted with 75 pound radial and 25 pound thrust load.

and the stabilizing treatments established for these materials are described in the Phase II Lubricant Development Section of this report.

In tests No. 8 through No. 13 all bearings were 20 mm bore size K162B roller bearings with five K162B load carrying rollers and five lubricant composite spacer rollers. The spacer rollers were designed to be 0.002 inches undersize at 1500°F. The results of these tests are also included on Table IV.

In addition to the high vacuum tests cited above, eight tests were conducted in air. These tests, which were funded by Boeing sponsored research, were conducted on a Pope tester to evaluate the lubricant composite spacer rolling element design under lower speed, load and temperature conditions. Table V in this section of the report includes the details of this investigation.

Tests No. 14 through No. 18 were conducted under the redirected program. In these tests lubricant composite materials were fabricated into a separator design. Three roller and two ball bearing tests were conducted. Table VI is a tabulation of these test results.

The results of all tests conducted, an analysis of the bearing failures, and comments applicable to each series of tests are described in the following discussion:

BEARING TESTS - NO. 1 THROUGH NO. 7 (TABLE IV)

Test 1 - In the first test, lubricant composite No. 18 (80% MoS_2 + 10% PbS + 10% Ni) shown on Table XVI was used as the spacer-rolling element. A catastrophic failure occurred after 1 minute and 30 seconds of operation. Rotation was initiated at 1470°F. During the test period the shaft accelerated to 11,000 rpm. At the time of failure, the temperature had increased to 1850°F. The pressure varied from 1×10^{-3}mm Hg to 8×10^{-5}mm Hg during the test period. Starting friction and running friction were 0.062 and 0.041, respectively. The bearing radial play before test was 0.0028 inches. After test the radial play had increased to 0.0076 inches. Based upon the 1 minute and 30 seconds of operation, the wear rate was 0.304 inches per hour.

Examination of the bearing after test revealed that all lubricant rollers had disintegrated. The bearing was filled with powdered molybdenum disulfide. The test chamber interior was coated with some products of the lubricant composite. At the maximum temperature and pressure conditions, the vapor pressure of the lead sulfide exceeded the ambient pressure in the test chamber and caused the lubricant roller disintegration.

Test 2 - In test number two, the lubricant roller was composite No. 28 (80% MoS_2 + 10% graphite + 10% Ni). After 3 minutes and 45 seconds of operation the bearing seized. The shaft had accelerated to 12,000 rpm. The temperature increased from 1475°F at the start to 1800°F at the time of bearing failure. A minimum pressure of 5×10^{-4}mm Hg was obtained. Starting friction was 0.015. Running friction was not obtained due to a recorder malfunction. Prior to testing the radial play was 0.0028 inch.

Examination of the bearing after test indicated a build-up of lubricant film on raceways and rollers. The build-up on the inner race diameter was 0.0039 inch. On the outer race diameter the build-up was 0.0017 inch. An average build-up of 0.0009 inch was indicated on the carbide rollers. This combined build-up on all surfaces caused an internal interference of 0.0037 inches. This factor was considered to be the cause for bearing failure.

Test 3 through Test 6 - In each of these tests, the bearing froze at the 1500°F test temperature before rotation began. On lowering the temperature from 1500°F, rotation of each bearing was possible. The spacer-roller diameters ranged from 0.4000 to 0.4050 inch. The temperature at which rotation was possible was found to be directly related to the spacer-roller diameter. Seizure for the bearing with 0.4050 inch diameter spacer-rollers occurred at 650°F. The bearing with .4000 inch diameter spacer-rollers seized at 1300°F.

Test 7 - In this test, lubricant composite No. 43 was used as the spacer-rolling element. In order to investigate operation at temperatures below 1500°F, rotation was initiated at 70°F. The temperature was increased at the rate of 110°F per minute. After 5 minutes and 42 seconds of operation a high friction was indicated. The temperature had reached 700°F. Examination of the bearing after test revealed a complete disintegration of the lubricant composite spacer-rollers.

Comments Applicable to Tests No. 1 Through No. 7

Due to the lack of thermal expansion data for molybdenum disulfide, the initial spacer-roller design had been predicated upon the expansion of the binder material in the compact. However, the expansion coefficient of the spacer-roller material greatly exceeded that of the carbide bearing material. The coefficient of linear thermal expansion of the spacer-roller material was calculated from the relationship between the spacer-roller diameter and the seizure temperature. The average value of this coefficient for the 90% lubricant and 10% binder material is 18.2×10^{-6} in/in/°F. Using this value, the maximum spacer-roller diameter to prevent seizure at 1500°F was calculated to be 0.396 inches. It is recognized that varying either the lubricant and binder materials or their ratios would affect the expansion coefficient.

The high thermal expansion of the spacer-rollers contributed significantly to the bearing seizure. Adjustments in roller diameter to compensate for high thermal expansion was expected to prevent recurrence of seizure in future bearing tests.

BEARING TESTS NO. 8 THROUGH NO. 13 (TABLE IV)

Test 8 - Testing of this bearing was initiated at 1500°F in a vacuum of 2.5×10^{-5}mm Hg. After 12 seconds of operation the test was terminated due to excessive friction. A maximum speed of 8000 rpm was attained. The vacuum level in the chamber had decreased to a value of 1.0×10^{-3} mm Hg. Examination of the bearing components after the test indicated the following:

Outer Race - A bright oxide film was apparent on all surfaces. The bore diameter decreased 0.0009 inch due to lubricant build-up. A highly burnished raceway and thrust face surface was evident.

Inner Race - The oxide film was evident on all surfaces. The raceway was highly burnished but with no measurable lubricant build-up. The thrust face showed a significant evidence of scoring as a result of thrust loading. Galling in the bore indicated evidence of rotation on the shaft.

TiC Rollers - The carbide rollers were oxidized and showed evidence of lubricant build-up on the diameter. The average diameter increase was 0.00033 inch. The roller ends in contact with the outer race thrust face were highly polished. The opposite roller ends in contact with the inner race thrust face showed significant scoring on each roller.

Lubricant-Composites - The composite rollers were highly burnished on their diameters. The roller ends in contact with the outer race thrust face were highly polished. The roller ends in contact with the inner race thrust face were lightly scored. The lubricant-composite roller diameter showed an average increase of 0.00040 inch after test.

Radial Play - Prior to test, the radial play was 0.00225 inch. After test the radial play had decreased to 0.00069 inch.

Test 8 - Probable Failure Cause: The high friction indication was judged to be due to the carbide roller and inner race thrust face scoring. The cause for this scoring condition has been investigated. The fact that the outer race thrust face was highly burnished indicates adequate outer race thrust face lubrication from the lubricant-composite. Due to the difference in curvature, the stress of the roller on the outer race is less than the stress on the inner race. The outer race thrust face roller stress is 580 psi compared to 660 psi for the inner race thrust face roller stress. It was considered that this difference in stress was not sufficient to have caused the significant scoring on the inner race thrust face while the outer race was in perfect condition. One possible sequence of events leading to failure is as follows: (1) high friction on the inner race thrust face caused increased slippage and rotation of the inner ring on the shaft. (2) The frictional heating due to rotation in the bore resulted in expansion of the inner race with a subsequent loss of clearance with the resulting high friction.

The examination of the rollers indicated a large contact area with the inner race thrust face and a relatively small contact area with the outer race thrust face. A close examination of the outer race revealed an outward taper on the thrust face. The effective thrust shoulder height was found to be approximately 0.020 inches. The effective shoulder height specified on the drawing for the outer race was 0.064 inches. This decrease in thrust shoulder height has two significant effects: (1) The stress level increased from 580 psi to about 3000 psi. (2) The sliding velocity between the roller and the thrust face was reduced by a factor of about 3. As the thrust shoulder height decreases, the sliding velocity also decreases. From this test it is apparent that with dry film lubrication, the higher operating stress at a low surface velocity is preferable to the low operating stress and higher surface velocity.

Another potential problem that was evident in this test is the decrease in radial clearance due to lubricant build-up on the raceway and rollers. If operation had extended over a longer time period, the bearing would have probably failed due to the reduction in internal clearance.

Test 9 - The bearing for this test was scheduled for operation in vacuum at 1500°F. The bearing was installed in the test fixture and a vacuum of 2×10^{-5}mm Hg was attained. When the temperature reached 1500°F, an initial indication of bearing friction was obtained by hand rotation of the test spindle. On the first partial shaft rotation, a high friction reading was evidenced. After several additional hand spins, the bearing seized. No attempt at powered operation was made.

Test 9 - Probable Cause of Failure: Upon removal from the test chamber, the cause for high friction was evident. Three of the lubricant-composite rollers had fractured radially in planes perpendicular to the central axis of the rollers. One had fractured into 7 separate discs. Two were intact. The records indicate that the composites were fabricated from three separate slugs (No's. 353, 377 and 378). In reviewing the hot pressing data, an unusual event was noted during the hot pressing of slug number 378. During this hot pressing operation, a burnout of the furnace occurred at 610°F. The die was allowed to cool and was subsequently hot pressed after a new heating element was installed. This initial preheating may have altered the physical properties of the material to the extent that failure resulted during the high temperature-high vacuum exposure.

Prior to fabrication, the slugs were heat-treated by exposure to 1800°F for 4 hours in an argon atmosphere. This factor indicates that the high temperature in itself was not detrimental to the composite material but that the combined effects of high vacuum and high temperature caused the failure.

Test 10 - This test was initiated at 1400°F in a vacuum of 1×10^{-4}mm Hg. During initiation of rotation, a partial loss of vacuum occurred in the test chamber. The duration of the low vacuum period was approximately two seconds. The initial friction reading was 0.025. In order to avoid any detrimental effects from rapid acceleration, the speed was gradually increased. After the 48 seconds of operation, and at 4000 rpm, the friction had increased excessively. The test was terminated.

The examination of the bearing after test indicated the following:

Outer Race: No lubricant build-up was evident on the outer race. In the non-contact areas an oxide film was evident. The measured radial wear was 0.00065 inches. Very light scoring was indicated on the thrust face.

Inner Race - No wear could be measured on the inner race. A visible very thin film of lubricant was in evidence. However, it was not of sufficient thickness to indicate a dimensional change. Light scoring was in evidence on the inner race thrust face.

TiC Rollers - The carbide rollers were coated with a dry shiny oxide film. The average roller wear was 0.00071 inches. Scoring was in evidence on both roller ends. The entire contact zone with the inner race was scored. The outer 25% of the theoretical contact area with the outer race showed evidence of scoring.

Lubricant-Composites - The lubricant-composites were in excellent condition. All contact surfaces were covered with a dark shiny film. The average composite wear was 0.00058 inches.

Radial Play - Before test the radial play was 0.0015 inches After test the radial play had increased to 0.00357 inches.

Test 10 - Probable Cause of Failure: The high friction which was the cause for bearing failure was probably directly due to the scoring of the ends of the rollers. This scoring as well as the high wear of the rollers and outer race is indicative of ineffective lubrication by the lubricant-composite rollers under the high vacuum-high temperature environments.

Test 11 - This test was conducted after tests 8, 9, 10, 12 and 13 had been completed. These tests had indicated that the thrust load may have contributed to an early failure in this design. Also, in these tests the self-induced temperatures were exceeding the temperature at which the lubricant-composites had been stabilized. For these reasons, Test 11 was conducted under lighter loads and at room temperature in a vacuum. The test was initiated in a vacuum of 5×10^{-6}mm Hg. The thrust load was reduced to 2 pounds. During the initial 30 seconds of operation, a friction coefficient of 0.02 was measured. After the initial 30 seconds, the friction indication increased rapidly. Upon completion of 1 minute and 30 seconds of operation the test was terminated due to the excessive friction (approximately 0.10). The maximum speed was 8000 rpm.

Examination of the bearing components after test indicated the following:

Outer Race - A light coating of lubricant film was evident in the raceway. The measured build-up was 0.00005 inches. The thrust face was highly polished with a mirror-like film of lubricant.

Inner Race - A light lubricant film was evident on the raceway and thrust face. The raceway build-up was measured as 0.00025 inches. The thrust face showed evidence of very slight scoring.

TiC Rollers - The carbide rollers were coated with a lubricant film 0.00068 inches thick. The roller end in contact with the outer race showed virtually no evidence of contact. The contact area was limited to a circumferential zone about 0.005 inches in width on the outside diameter. The roller end loaded by the inner race showed a full contact area with very light scoring in evidence.

Lubricant-Composites: The composite rollers had a glazed burnished appearance. One roller was broken in two pieces. It had a circumferential fracture about 0.150 inches from the roller end which was loaded by the inner race thrust face. All other rollers were intact. The roller ends loaded by the outer race were slightly chipped. The ends loaded by the inner race were glazed and burnished.

Radial Play - Before test the radial play was 0.0033 inches. After test the radial play had decreased to 0.00165 inches.

Test 11 - Probable Failure Cause: The fractured lubricant-composite was the probable final cause for excessive friction. The initial friction increase and composite fracture may have been due to the debris from the chipping of the lubricant-composite roller ends. This chipping probably resulted from the lubricant build-up in the thrust face to raceway corner. If the rate of lubricant build-up is linear, the bearing would have probably failed after 3 minutes of operation due to lubricant build-up.

Test 12 - Test 12 was initiated at 1500°F in a vacuum of 1.5×10^{-5}mm Hg. An excessive friction indication resulted in test termination after 72 seconds. The maximum temperature indicating capability of the recorder (1800°F) was reached after about 60 seconds of the test. The maximum speed was approximately 10,000 rpm. Upon examination of the bearing after test, three significant changes were evident: (1) The inner race was fractured circumferentially near the thrust face edge. (2) The ends of the lubricant-composite rollers in contact with the inner race were all badly chipped and broken, and (3) All rollers and races were coated with a mirror-like layer of lubricants. Photographs showing 7X and 10X magnification of the failed bearing components are shown on Figures 4, 5, 6 and 7.

The detailed examination indicated the following:

Outer Race - The outer race lubricant coating resulted in a diameter decrease of 0.0008 inches. The thrust face was highly burnished with no evidence of scoring.

Inner Race - The inner race diameter increased 0.0006 inches as a result of lubricant build-up. The thrust face lubricant build-up was evident on the surface nearest the minor diameter. The outer half of the thrust face did not have a lubricant coating; very light scoring was evident on this surface. Light scoring in the bore was evidence of rotation between the bore and shaft.

TiC Rollers - All carbide rollers showed evidence of a heavy build-up of the mirror-like lubricant coating. The average roller diameter increase was 0.00152 inches. All carbide roller ends in contact with the outer race showed no evidence of scoring but were highly burnished over 25% of the theoretical contact area. The roller ends which contacted the inner race showed evidence of scoring over the entire contact surface.

Lubricant-Composites - All lubricant-composites were highly burnished on their diameters and on the end in contact with the outer race. The ends in contact with the inner race thrust face were all badly chipped and scored. The lubricant-composites indicated an average diameter increase of 0.00062 inches. This growth may be attributed to the fact that the pre-test heat treatment for dimensional stability was conducted at 1800°F and that, in test, a temperature in excess of 1800°F was attained.

Radial Play - The radial play before test was 0.0018 inches. Due to the lubricant build-up, no radial play was indicated after test. The build-up resulted in an internal interference of 0.00264 inches.

Test 12 - Probable Failure Cause: The failure in this test may be attributed to the loss of internal clearance due to lubricant build-up and/or the deterioration of the lubricant-composite in contact with the inner race.

Test 13 - This test was initiated at 1500°F in a vacuum of 3×10^{-5}mm Hg. After 51 seconds of operation the test was terminated due to excessive friction. A maximum speed of 7000 rpm was attained. Examination of the bearing components after test indicated the following:

Outer Race - The outer race was coated with a dark shiny lubricant film on all contact surfaces. This build-up was measured to be 0.0001 inches. The thrust face was in good condition. Due to the high internal stresses caused by the lubricant build-up, two small sections (0.060 inches wide) were broken from the outside edge of the raceway on disassembly of the bearing after test.

Inner Race - The raceway was coated with the dark shiny lubricant film. The thrust face was very lightly scored. Score marks indicative of shaft rotation were evident in the bore. The lubricant film build-up increased the raceway diameter by 0.00035 inches.

TiC Rollers - All roller diameters were coated with the dark, shiny lubricant film. The average roller diameter increase was 0.0013 inches. The roller ends in contact with the outer race showed evidence of light scoring. The roller ends in contact with the inner race showed evidence of heavier scoring. All roller ends were chipped on an average of 0.125 inch on the circumference.

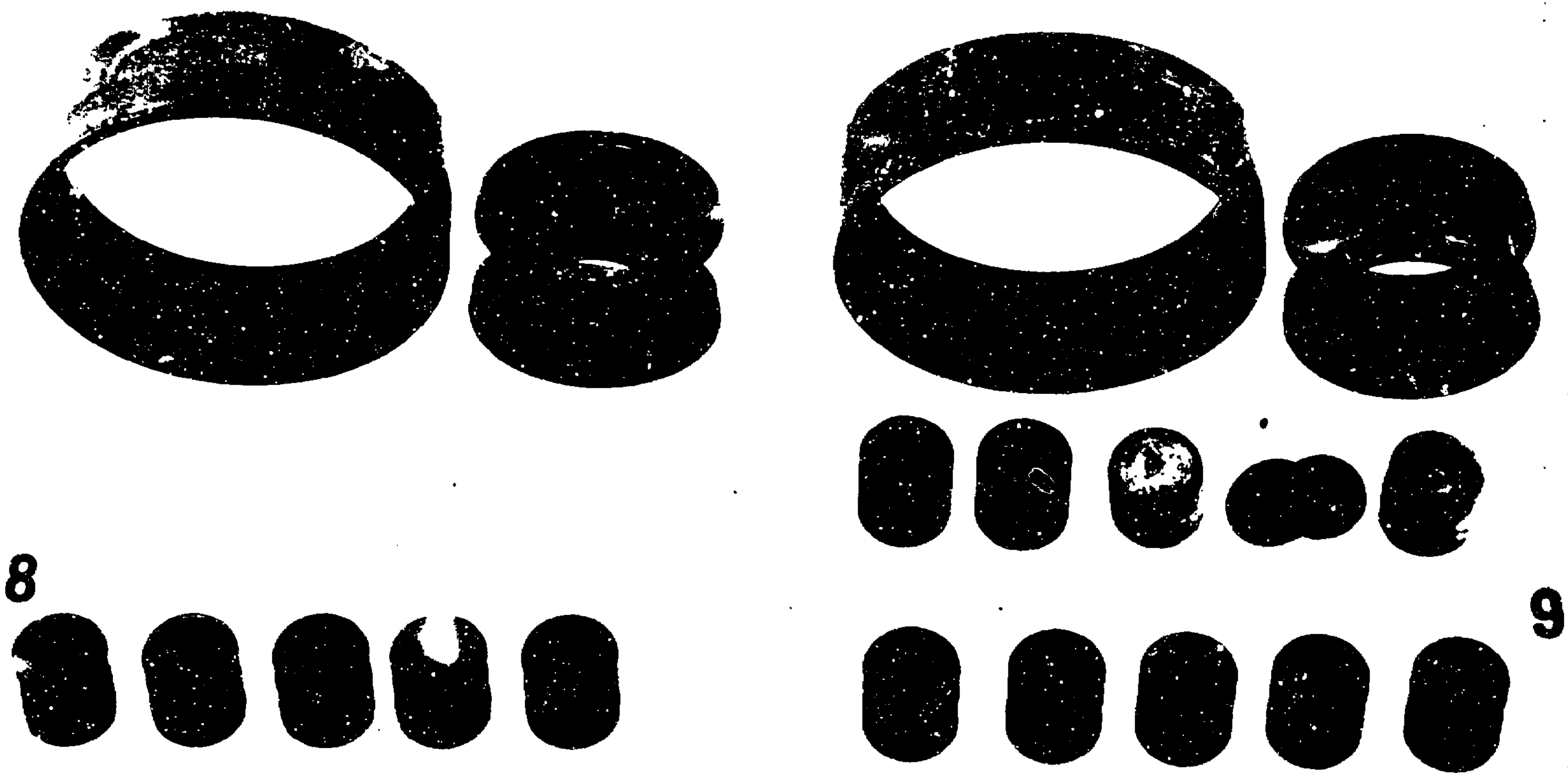


FIGURE 19 FAILED ROLLER BEARING TESTS 8 AND 9

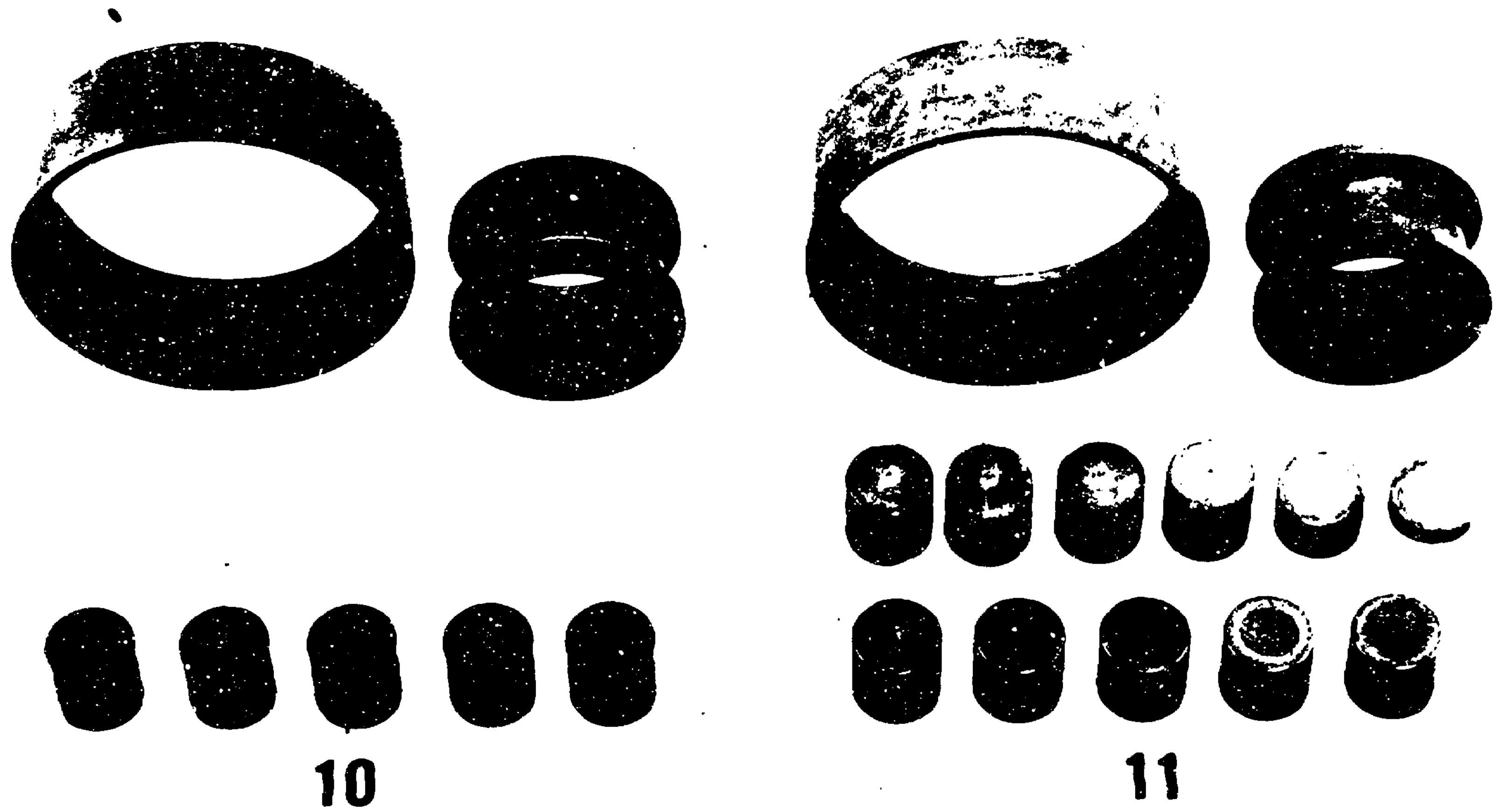


FIGURE 20 FAILED ROLLER BEARING TESTS 10 AND 11

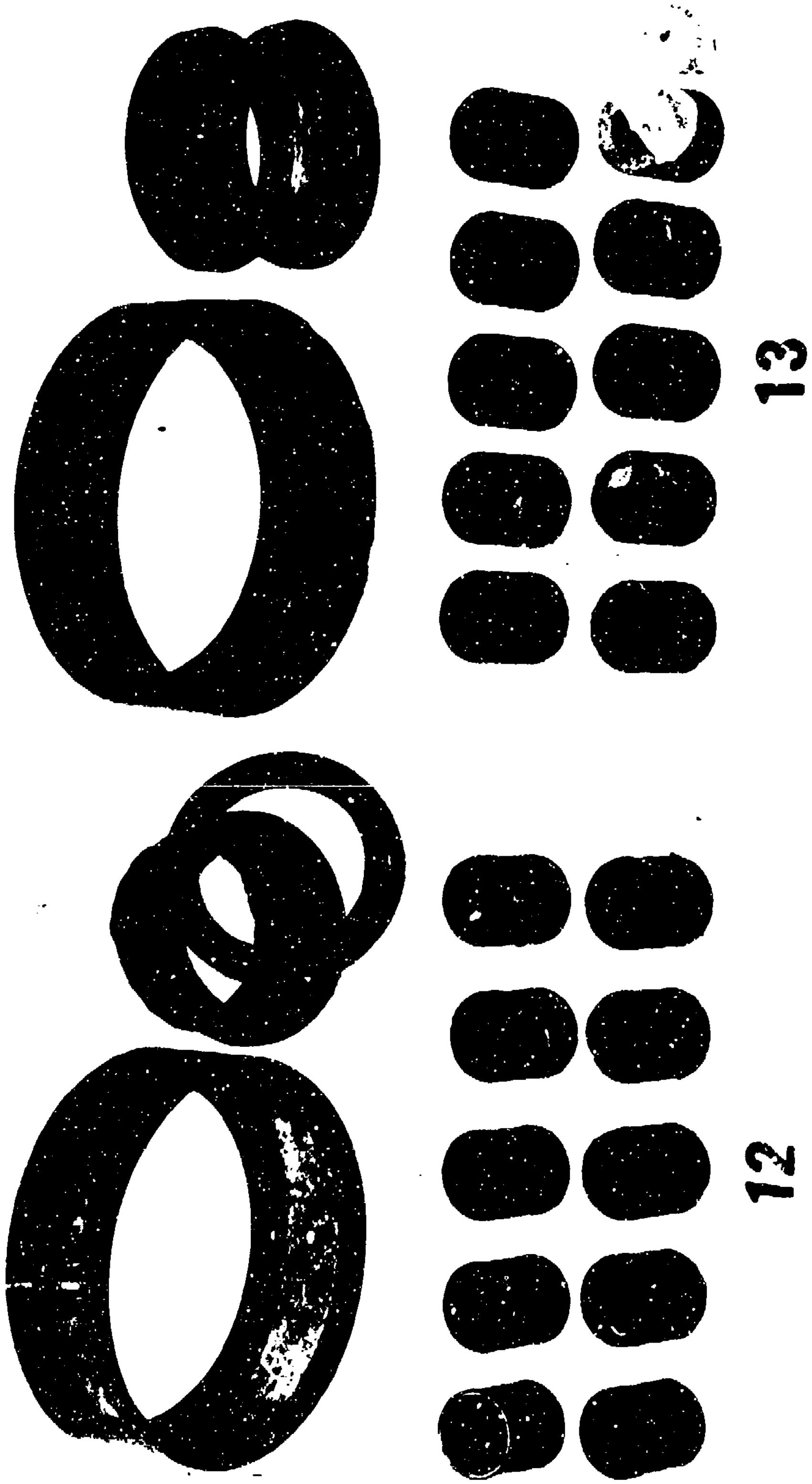


FIGURE 21 FAILED ROLLER BEARING TESTS 12 AND 13

Lubricant-Composites: The lubricant-composites diameters were all coated with the dark shiny lubricant film. An average diameter increase of 0.0003 inches was measured. The ends in contact with the outer race were chipped around approximately 15% of the circumference. One composite was fractured across the end to the mid-point of the roller. Another had fractured approximately over 25% of the end surface.

Radial Play: The radial play before test was 0.00194 inches. No radial play existed after test due to the lubricant build-up. The measurements indicated a 0.0010 inch internal interference after test.

Test 13 - Probable Failure Cause: In this test the lubricant build-up with the subsequent loss of internal clearance is considered to be the primary cause of failure. The scoring of the lubricant-composite's ends and debris resulting from their end chipping may also have contributed to the bearing failure.

After testing, each bearing component was dimensionally checked and visually examinated under 20X and 80X magnification. Photographs of the failed bearings are shown in Figures 19, 20 and 21.

None of the bearings in tests No. 8 through No. 13 exhibited satisfactory performance under high vacuum conditions.

None of the lubricant-composites tested in vacuum provided lubrication comparable to previous graphite spacer roller tests in air.

Lubricant build-up on the raceways and rollers was one of the contributing causes for excessive bearing friction and failure.

Roller end and inner race thrust face scoring were other important causes for excessive friction and failure.

Roller end chipping may be due to high local stresses caused by lubricant build-up in the thrust shoulder to raceway corners.

With the marginal lubrication capability of the composites tested, the reduced thrust shoulder height, apparent on the outer races, significantly reduced roller end scoring.

BEARING TESTS IN AIR (TABLE V)

The bearing tests conducted in air have illustrated some of the deficiencies which result from the spacer rolling element bearing design. Ball bearing tests 1, 2 and 3 resulted in excessive wear of the lubricating spacer balls. This wear was not a uniform diameter reduction but resulted in a grooved wear zone around the diameter in contact with the steel load carrying balls.

Test 4, which had a full complement of Teflon balls, resulted in a general diameter reduction rather than the grooved wear which resulted from the previous tests. The high spacer ball wear in tests 1 through 3 was attributed,

TABLE V

BEARING TESTS IN AIR

No.	Type	Lubs Element	No. of Elements	Temperature °F	Speed (rpm)	Revolutions Per Run	Total Revolutions	Time (hrs)	Type of Failure
1	Ball	Graphite Balls	6 graphite 6 steel	Room 600	10,000 10,000	600,000 1,8000,000	2,400,000	1 3	No failure: test continued at 600°F Debris from wear of graphite balls
2	Ball Ball	Graphite Balls Graphite Balls	6 graphite 7 steel	Room 570	5,000 5,000	48,000 30,000	780,000	1.6 1	Jammed from wear debris (graphite). Bearing removed and cleaned, test continued. Graphite balls broken.
3	Ball	Teflon balls	6 teflon 6 steel	460	3,600	432,000	432,000	2	Considerable wear of teflon balls.
4	Ball	Teflon	13 teflon	Room	3,600	216,000	216,000	1	Wear of balls caused excessive radial play; shaft rubbing housing.
5	Roller	Rulon	5 Rulon 5 TiC	500	1,800	594,000		5.5	Noisy; stopped test and cleaned bearing; test resumed.
	Roller	Rulon	5 Rulon 5 TiC	Room	1,800	324,000		3	No failure; testing continued at 500°F.
	Roller	Rulon	5 Rulon 5 TiC	500	1,800	3,078,000		28.5	Stopped due to noise. Considerable wear debris. Cleaned bearing and resumed test.
	Roller	Rulon	5 Rulon 5 TiC	Room	10,000	60,000	4,056,000	.1	Stopped due to noise and vibration.
6	Roller	No. 203 composite No. 220 composite	5 5	Room	1,800 3,600	9,000 18,000	27,000	5 min. 5 min.	No failure; test continued at 3600 rpm. Noisy; heavy lubricant build-up.
7	Roller	No. 203 composite TiC	5 5	Room	1,800	162,000	162,000	1.5	Rapid temperature rise; noisy; lubricant debris.
8	Roller	No. 203 composite TiC	2 8	Room	1,800 3,600 10,000	18,000 36,000 250,000	304,000	10 min. 10 min. 25 min.	No failure; test continued at 3600 rpm. No failure; test continued 10,000 rpm. Noisy, vibration; inadequate lubrication.

in part, to the high stress associated with point contact between the spacer and load carrying balls. The low strength of the graphite and the Teflon also contributed to the high wear.

In test 5, the higher strength "Rulon" (reinforced Teflon) was fabricated into spacer rollers which also would provide the lower stress line contact condition. In all runs in Test 5, the test was terminated due to the significant increase in bearing noise level. Examination of the bearing after each run indicated a Teflon film build-up on all surfaces. No measurable wear resulted on either the inner or outer raceway after completion of the total 4,056,000 revolutions. The average carbide roller wear after test was 0.00015 inches. The Rulon spacers average wear was 0.009 inches. All contact surfaces of the bearing were highly polished coated with the Teflon film.

In tests 6, 7 and 8 two of the lubricant-composites (No's. 203 and 220) which had been used in the high vacuum bearing tests previously discussed, were evaluated.

In Test 6, the lubricant-composites were used as load carrying rollers. After the short run, 27,000 revolutions, sufficient lubricant build-up and debris had occurred on the raceways to cause the high noise level and test termination. The raceways used in Test 6 were cleaned and reinstalled in the test machine with five carbide load carrying rollers and the No. 203 lubricant-composite as spacer rollers for Test 7.

Test 7 showed an improvement (162,000 revolutions) over Test 6, but again the lubricant build-up and debris formation resulted in a high noise level with test termination. The raceways were again cleaned and reinstalled in the test machine for Test 8.

In Test 8, only two No. 203 lubricant-composites were used with eight load carrying carbide rollers. The performance of this bearing (304,000 revolutions) was significantly better than Tests 6 and 7. Examination of the bearing races after test showed no evidence of lubricant build-up. Light scoring was evident on the inner race thrust face and the contacting roller ends.

Comments Applicable to Bearing Tests in Air:

The tests in air indicate the feasibility of the roller bearing design for operation at temperatures to 500°F with a Teflon lubricating composition.

None of the lubricant-composites tested in vacuum provided lubrication comparable to the Teflon spacer roller test in air.

The in-air tests with two lubricant-composites provided superior performance to the tests with 5 spacer composites.

The grooved wear zones which occurred on the lubricating spacer balls indicate limitations of the lubricant-composite spacer rolling element separator in the ball bearing design.

BEARING TESTS NO. 14 THROUGH NO. 18 (TABLE VI)

Test 14 - This test was planned as a load and speed spectrum evaluation of the lubricant composite separator design for the roller bearing. Testing was initiated with a 37-1/2 pound radial load, a 12-1/2 pound thrust load, and 5000 rpm at 1500°F in a vacuum of 5 x 10^{-6}mm Hg. The test was terminated due to a high friction indication after 6 minutes of operation. Figure 22 is a photograph of this bearing after test.

Separator design - As shown in Figure 22 the configuration of the lubricant composite material used in this separator differs from the configuration shown on Figure 16. In this design the lubricant composite material (No. 99 on Table XVI) was machined to provide a conforming area contact with the rollers. The flange thickness on the composite material was 0.060 inch. In this separator design, as well as in all others tested, Inconel X cage rings with connecting Rene' 41 pins were used as the main supporting structure (see Figures No. 16 & 18). The pins, which were designed for a rivet attachment, were electron beam welded to the rings to facilitate fabrication.

The radial play before test was 0.0015 inch.

Slight rotation of the inner race on the test shaft while under vacuum conditions resulted in a seizure between the shaft and bearing bore. As a result the thrust face of the inner race was fractured on removal from the shaft. Examination of the bearing after test showed a lubricant build-up on the inner and outer races and on the rollers. The radial play had been reduced to zero. The flanges of the lubricant composite materials had fractured. Corners of the flanges on the other lubricant composite materials were chipped. No wear or scoring was evident on the rollers or raceways.

Test 14 - Probable Failure Cause: The high friction indication was attributed to the reduction in bearing internal clearance due to lubricant build-up on the raceways and rollers.

Test 15 - This roller bearing test was planned for operation under test conditions identical to Test 14. The bearing seized when rotation was attempted at 1500°F. Upon lowering the temperature to 1000°F rotation of the bearing was possible. Ten seconds after rotation was initiated at 1000°F the bearing seized. Figure 23 is a photograph of this bearing after test.

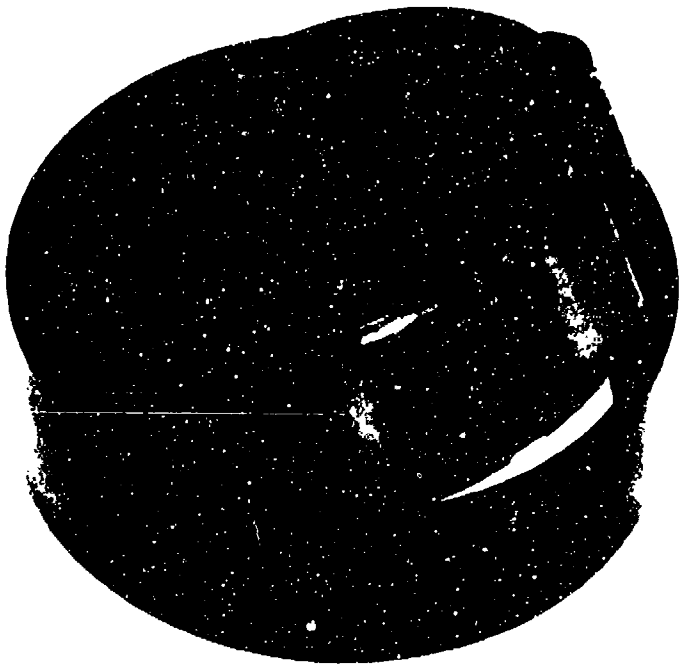
Separator Design - In an attempt to reduce the amount of lubricant build-up obtained in Test 14 the configuration of the lubricant composite material was modified. As shown in Figures 22 & 23 the area roller contact of the Test 14 separator was reduced to line contact in the Test 15 separator. This was accomplished by machining the ends of the lubricant composite material to provide a plane surface coincident with a radial plane through the bearing. Because of the brittle material characteristics (No. 425 on Table XVI) the flanges of the lubricant composites were broken during fabrication.

The radial play before test was 0.0017 inch.

TABLE VI

PHASE II REDIRECTED PROGRAM BEARING TESTS

TEST NO	BEARING TYPE	SEPARATOR MATERIAL	LOAD IN LBS. RADIAL	LOAD IN LBS. THRUST	VACUUM mm HG	TEMP °F START	TEMP °F MAX.	FRICTION START	FRICTION RUN	SPEED RPM	REVOLUTIONS PER RUN	TIME PER RUN	TOTAL REVOLUTIONS	TOTAL TIME	REMARKS
14	Roller	No. 99	37 1/2	12 1/2	5×10^{-6}	1440	1500	.044	.033	5000	30,000	6 min.	30,000	6 min.	Test terminated due to high friction indication - no wear lubricant build upon inner race.
15	Roller	No. 425	37 1/2	12 1/2	4×10^{-5}	1000	---	---	---	1500	250	10 sec.	250	10 sec.	High initial friction - lube composite pivoted in separator and jammed rollers.
16	Roller	No. 144	37 1/2	12 1/2	1×10^{-4}	250	295	---	---	5000	150,000	30 min.			Test terminated due to high friction indication - flange on lube composite fractured - composite pivoted and jammed rollers. No scoring or measureable wear. Bearing surfaces excellent.
			37 1/2	12 1/2	5×10^{-6}	295	310	---	---	10,000	300,000	30 min.			
			37 1/2	12 1/2	1×10^{-4}	310	340	---	---	15,000	375,000	25 min	825,000	1 hour 25 min.	
17	Ball	No. 99	37 1/2	12 1/2	1×10^{-4}	250	300	---	005	5000	150,000	30 min.			Test terminated due to false excessive friction indication caused by heater element contact with shaft. All bearing surfaces show high polish. No measureable wear. Flange corners on two lube composites chipped. Bearing in excellent condition.
			37 1/2	12 1/2	1×10^{-5}	300	310	.008	005	10,000	300,000	30 min.			
			37 1/2	12 1/2	2×10^{-4}	310	650	.009	013	15,000	450,000	30 min.			
			75	25	1×10^{-4}	200	560	---	.015	15,000	450,000	30 min.			
			75	25	1×10^{-5}	560	680	---	---	15,000	300,000	20 min.	1,650,000	2 hours 20 min.	
18	Ball	No. 144	37 1/2	12 1/2	1×10^{-5}	70	865	---	---	5000	150,000	30 min.			Test terminated due to high friction. All lubricant composites in separator were fractured.
			37 1/2	12 1/2	3×10^{-5}	865	1260	---	---	10000	50,000	5 min.	200,000	35 min.	



BEARING NO. 14

BEARING NO. 15

FIGURE 22 ROLLER BEARING NOS. 14 AND 15 AFTER TEST

Test 15 - Probable Failure Cause: Examination of the bearing after test revealed that the lubricant composite blocks had pivoted on the separator pins and jammed the adjacent rollers.

Test 16 - This test was planned as a combined load, speed and temperature spectrum evaluation of the roller bearing lubricant composite separator design. Changes in operating conditions were planned in successive step increments of 30 minutes.

In step one, testing was initiated with a 37-1/2 pound radial and a 12-1/2 pound thrust load at 5000 rpm. The bearing temperature was increased to 250°F prior to initiation of rotation. After operation for 30 minutes under these conditions the bearing temperature had increased to 295°F. The average running friction during this test was not obtained because of a strain gage failure. A vacuum of 1×10^{-4}mm Hg was attained during this run.

In the second step the speed was increased to 10,000 rpm. During the 30 minute run at this speed the temperature increased from 295°F to 310°F. A vacuum level of 5×10^{-6}mm Hg was attained during this period.

In the third step the speed was increased to 15,000 rpm. After 25 minutes of operation at this speed a high friction was indicated. During the run the temperature increased from 310°F to 340°F. The vacuum attained during this run was 1×10^{-4}mm Hg. A photograph of this bearing before final assembly is shown in Figure 23.

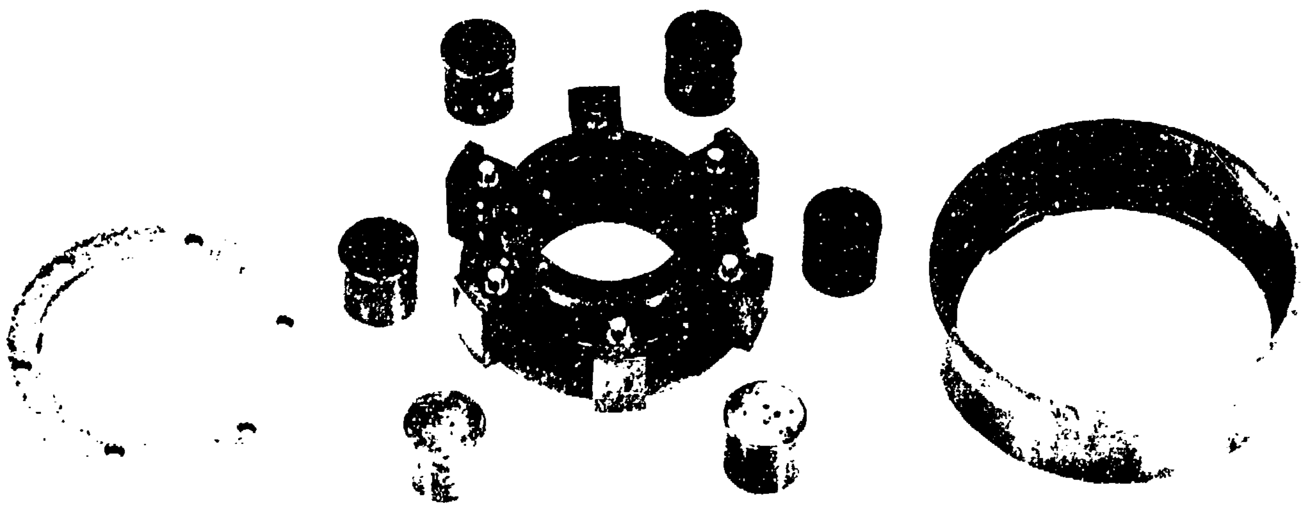


FIGURE 23 ROLLER BEARING NO. 16 BEFORE TEST

Separator Design - The design of the separator used in this test is shown on Figure 16. Because of the lubricant composite flange failures obtained in Test 14 and the apparent requirement for flanges to prevent the lubricant composite block from pivoting as indicated in Test 15, the design was modified for this separator. The flange was strengthened by increasing the thickness from 0.060 inch to 0.080 inch. The inner race contact distance was increased over the Test 15 separator to provide greater resistance to lubricant composite block pivoting. The lubricant composite material used for this separator was No. 144 on Table XVI.

Examination of the bearing after test showed the bearing to be in excellent condition. A thin (less than .0001 inch) film of highly polished dry lubricant was evident on all bearing surfaces. No measureable wear or change in radial play was evident. A flange on one lubricant composite separator block had fractured. This block had pivoted and jammed against adjacent rollers. Slight chipping of the lubricant composite blocks edges which were in contact with the inner race was evident.

Test 16 - Probable Failure Cause: Fracture of the lubricant composite flange and subsequent pivoting caused the high friction indication.

Test 17 - In this test a load, speed and temperature evaluation of the lubricant composite separator design for the ball bearing was planned. The sequence of operation as outlined for the roller bearing in Test 16 was followed. The bearing radial play before test was 0.0010 inch.

In step one testing was initiated with a 37-1/2 pound radial and a 12-1/2 pound thrust load at 5000 rpm. Prior to rotation the test temperature was 250°F. After 30 minutes of operation the bearing temperature was 300°F. The average friction coefficient and the vacuum attained during this run were 0.005 and 1×10^{-4}mm Hg, respectively.

In step two the speed was increased to 10,000 rpm. During this 30 minute run the temperature increased from 300°F to 400°F. The average running friction was 0.005. The vacuum level attained was 1×10^{-5}mm Hg.

In the third step the speed was increased to 15,000 rpm. Average friction during this 30 minute run was 0.013. The vacuum level attained was 2×10^{-4}mm Hg. During this period the temperature increased from 310°F to 650°F.

In step four the load was increased from 37-1/2 pounds radial and 12-1/2 pounds thrust to 75 pounds radial and 25 pounds thrust. The speed was maintained at 15,000 rpm. The average friction coefficient during this 30 minute run was .015. The temperature increased from 200°F to 560°F.

In step five the speed and load were maintained at 15,000 rpm and at 75 pounds radial and 25 pounds thrust. At the beginning of the run the temperature was 560°F. Full heater power was applied to increase the bearing temperature. Only a slight temperature increase was noted. After 15 minutes of operation in this step the erratic friction values were indicated. The test was terminated after 20 minutes of operation in step 5 due to an excessive friction indication. The bearing had completed a total of 2 hours and 20 minutes of operation under vacuum conditions.

Separator Design - The separator design used for this bearing is shown on Figure 18. The lubricant composite material was No. 99 on Table XVI.

The radial play before test was 0.0011 inch.

Examination of the bearing housing after test revealed that the heater element wire had been in contact with the test shaft. This had resulted in the erratic and high friction indication.

Examination of the bearing showed it to be in excellent condition. Balls and races were highly polished and appeared to be coated with a thin film of dry lubricant. No measureable dimensional change was evident on either balls or races. The cage pockets were highly burnished but showed no appreciable wear. The corners on one lubricant composite separator flange were chipped. The bearing was still in operable condition. The time remaining in the program did not permit additional testing of this bearing.

Test 18 - This test was planned to evaluate another ball bearing design with a different material in the lubricant composite separator. A test sequence identical to that used in Test 17 was planned. The bearing radial play before test was 0.0011 inch.

In step one operation was at 5000 rpm, with a 37-1/2 pound radial and a 12-1/2 pound thrust load. The temperature increased from 70°F at the beginning of test to 865°F after 30 minutes. The vacuum level attained in this period was 1×10^{-5}mm Hg. Friction measurements could not be obtained due to a strain gage malfunction.

In the second step the speed was increased to 10,000 rpm and the step one load was maintained. After 5 minutes of operation the bearing seized. The bearing temperature had increased from 865°F to 1260°F.

Examination of the bearing after test showed that all lubricant composite separator blocks had fractured through their center section. All void areas within the bearing were filled with pulverized lubricant composite material.

Test 18 - Probable Failure Cause: The disintegration of the lubricant composite material was the cause of bearing seizure. The reason for the lubricant composite material disintegration was not determined.

D. RADIATION TESTING

The following contractual requirement was originally specified for the Phase II program:

"Ten bearings shall be subjected to an integrated nuclear flux of 10^{-7} fast neutrons. --- While being subjected to irradiation, the bearings will be at 1500°F temperature. After subjecting the bearings to radiation, the bearings shall be dynamically tested---."

In order to fulfill the above requirement a subcontract was let for use of the nuclear reactor facility at Washington State University.

An irradiation container was fabricated to contain and heat the test bearings during exposure to nuclear radiation. Figure 24 shows the internal construction and materials used for the container. The container components and the assembly are shown in Figure 25. The materials used for the container were selected on the bases of chemical compatibility, thermal stability, minimum thermal neutron cross-section, availability, and minimum cost.

A simulated environment test was conducted to check out the radiation container. A test bearing instrumented with thermocouples was placed inside the chamber and the container lid and heater were installed. The entire assembly was then submerged under four feet of water to simulate conditions in the reactor. The test bearing was heated to 1500°F for ten hours. During this time, the bearing's inner race temperature stabilized at 1550°F and the outer race at 1450°F. Throughout the test, air was circulated through the container at approximately 100 cu. ft/hr. Immediately after testing, the exterior temperature of the container was less than 150°F. Inspection of the disassembled container showed no defects. Upon completion of the simulated test the radiation container was considered to be satisfactory for use in the nuclear reactor test.

Included in the redirected contract effort was the cancellation of the nuclear radiation exposure. As a result no bearing testing after exposure to radiation was possible.

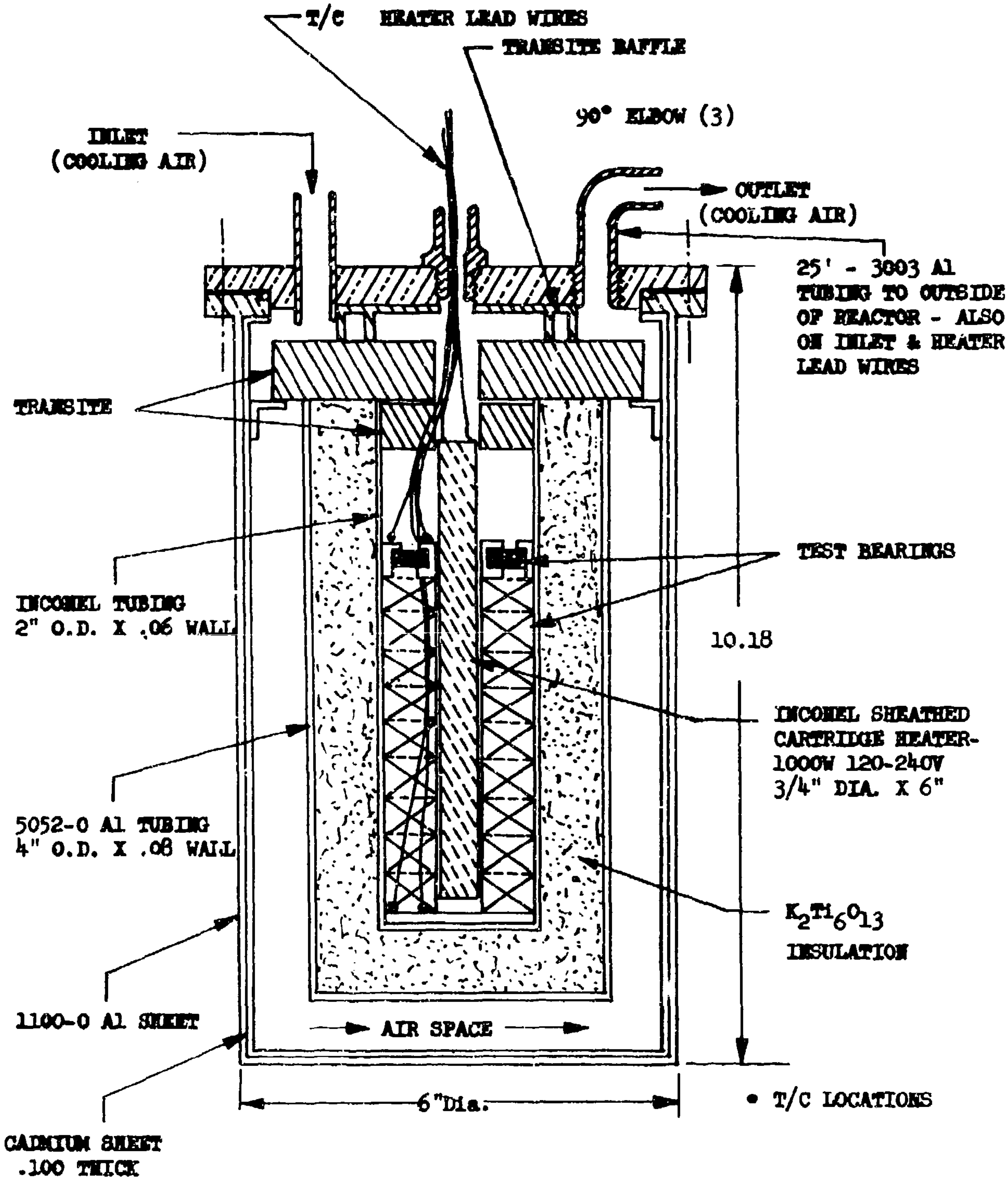


FIGURE 24
BEARING CONTAINER FOR RADIATION EXPOSURE

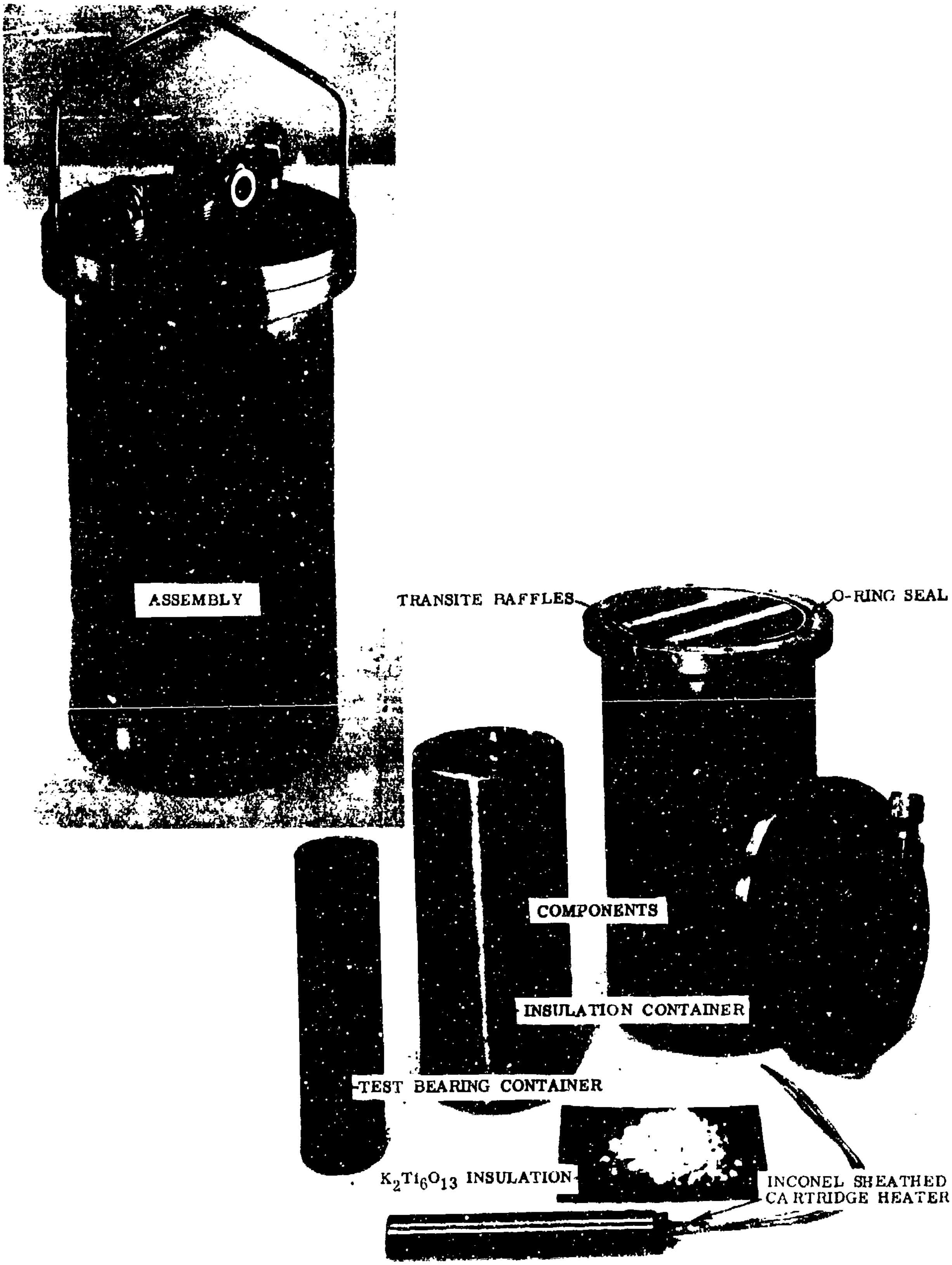


FIGURE 25 BEARING CONTAINER FOR RADIATION EXPOSURE - COMPONENTS AND ASSEMBLY

E. PHASE II CONCLUSIONS

1. The Phase I bearing designs which demonstrated feasibility of operation in 900°F air were unsatisfactory when operated in the vacuum environment.

2. The lubricant composite materials did not perform satisfactorily when used as spacer rollers under vacuum conditions.

3. A new and unique bearing design concept which utilized a lubricant composite material as the cage resulted in successful vacuum operation for both ball and roller bearings.

4. The feasibility of the lubricant composite cage design for high speed operation with dry lubricant films in the vacuum range of 10^{-4}mm Hg to 10^{-6}mm Hg was demonstrated in Phase II roller bearing test 16 and ball bearing test 17. No wear, scoring or pitting was evident in either the roller or ball bearing after test.

5. The best vacuum performance, 2 hours and 20 minutes of operation at speeds of 5000, 10,000 and 15,000 rpm, was obtained in the ball bearing separator design using the dry lubricant composite material No. 99 which was 90% by weight molybdenum disulfide, 8% iron and 2% platinum.

6. The configuration of the lubricant composite material in the separator was the most critical factor insofar as success or failure of the roller bearing design was concerned.

7. Substantial improvements in bearing vacuum performance were obtained by refinements in cage design and by changes in the lubricant composite compositions.

MATERIALS SECTION

TABLE LXXV

PHASE I LUBRICANT DEVELOPMENT

Air Force Contract AF 33(616)-7395

"DEVELOPMENT OF DESIGN CRITERIA FOR A DRY FILM LUBRICATED BEARING SYSTEM"

In accordance with the requirements of Exhibit B, Appendix 1 of the contract cited above, the following material development section is included in this report.

1. INTRODUCTION

The objective of the lubricant development effort was to obtain a dry film system capable of lubricating bearing surfaces at 900°F and 1500°F. Six proprietary high temperature lubricants were suggested by ASD for evaluation in the program. Several additional dry film systems, which have demonstrated high temperature potential, have been evaluated. Lubricant development and evaluation were conducted under two development programs for the conditions of load, speed, radiation and temperature specified by the original contract. One program, investigation of inorganic dry film and binder materials was conducted in the Boeing laboratories. A supplementary dry film development program was conducted by Washington State University.

2. LUBRICANT DEVELOPMENT

The Boeing Company

a. Lubricant Coatings

Work accomplished on Phase I of this contract includes the following coating formulation:

(1) NAMC - AML - 23A (Graphite, MoS_2 and Na_2SiO_3 Binder)

(2) BAC 7 glass binder + PbS

(3) PbS + B_2O_3

(4) PbS, MoS_2, B_2O_3 Coating

(5) BAC 8, Bi_3O_2 + Ag

(6) CaF_2 + Bureau of Standards A-418 Ceramic Adhesive

(7) PbO + Bureau of Standards A-418 Ceramic Adhesive

(8) CaF_2 + Ag + Bureau of Standards A-418 Ceramic Adhesive

(9) Ag-PbO Flame Sprayed

Formulas and complete preparations are outlined in Table X.
In addition the following commercial compounds were also evaluated:

(10) Dry Film Coating No. 1000

(11) Dry Film Coating No. 811

(12) Dry Film Coating No. M-1284

(13) Dry Film Coating No. 4396

b. Dry Film Lubricant Screening Test Equipment

(1) Falex Test

Initial test work on Phase I of this contract was done on the Falex Tester to select a suitable binder material. Three compositions using BAC-7 binder were selected on the basis of 16 Falex tests. Falex test results are summarized in Table VII.

(2) Boeing Galling Machine

Prior to obtaining the high speed bearing equipment necessary for this contract some tests were conducted on The Boeing Company Galling Machine. These tests were conducted at 3.5 feet per minute. Results are shown in Figure 26 and 27. An attempt was made to approach conditions found in high speed bearings by running the Galling Machine at 300 feet per minutes, with a 50 psi load. Results of these tests are included in Figure 27. On the basis of data obtained in this manner the PbS, Graphite, BAC-7 glass coating was selected as the best Boeing formulation for use at 900°F.

(3) High Speed Spindle

This equipment is a modified high speed spindle driven by a five horsepower 3600 rpm electric motor. The test spindle speed of 15,000 rpm is obtained in a single step up pulley with a nylon flat belt. The various components of the test set-up are shown in Figure 28.

TABLE VI

FALEX SCREENING TESTS OF DRY FILM LUBRICANTS

TEST NO.	LUBRICANT & %		BINDER & %		CURE	MAX. LOAD	FALEX TEST* FRICTION MIN	MAX	REMARKS
1	PbS	50	B_2O_3	50	10 minutes at 1200°F	1250	.557	.904	Slight scoring.
2	PbS Graph	25 25	B_2O_3	50	10 minutes at 1200°F	4500	.064	.115	No scoring on shafts and blocks.
3	PbS	25	BAC-7	75	10 minutes at 1050°F	1750	.33	.68	Slight scoring.
4	PbS Graph	25 25	BAC-7	50	10 minutes at 1050°F	4500	.069	.339	No scoring on shafts and blocks.
5			BAC-7	100	10 minutes at 105 1050°F	750	.79	1.36	Heavy scoring.
6	PbO	50	BAC-7	50	10 minutes at 1050°F	2000	.296	.69	Slight scoring.
7	PbO Graph	25 25	BAC-7	50	10 minutes at 1050°F	4500	.048	.271	No scoring on shafts and blocks.
8	Graph	50	BAC-7	50	10 minutes at 1050°F	1750	.113	.27	Slight scoring.
9	$CrCl_3$ Graph	25 25	BAC-7	50	10 minutes at 1050°F	1000	.65	.95	Scoring.
10	Graph PbO	33 33	Sodium Silicate	34	24 hours at 275°F	4500	.063	.34	No scoring on shafts.
11	AgCl Graph	25 25	BAC-7	50	10 minutes at 1050°F	4500	.10	.294	Slight scoring on shaft.
12	ZnO	30	BAC-7	70	10 minutes at 1050°F	500	1.07	1.35	Scoring.
13	BN	50	BAC-7	50	10 minutes at 1050°F	—	—	—	No adhesion.
14	BN	25	BAC-7	75	10 minutes at 1050°F	750	.715	1.13	Scoring.
15	Bi_2O_3	50	BAC-7	50	10 minutes at 1050°F	—	—	—	No adhesion.
16	Bi_2O_3 Graph	25 25	BAC-7	50	10 minutes at 1050°F	4500	.08	.226	No scoring on shafts and blocks.

*Standard Falex room temperature test. Inconel X U blocks and pins. Vacu blasted before application of dry film.
Test continued until torque reached 110 inch-lbs or 4500 pound load reached.

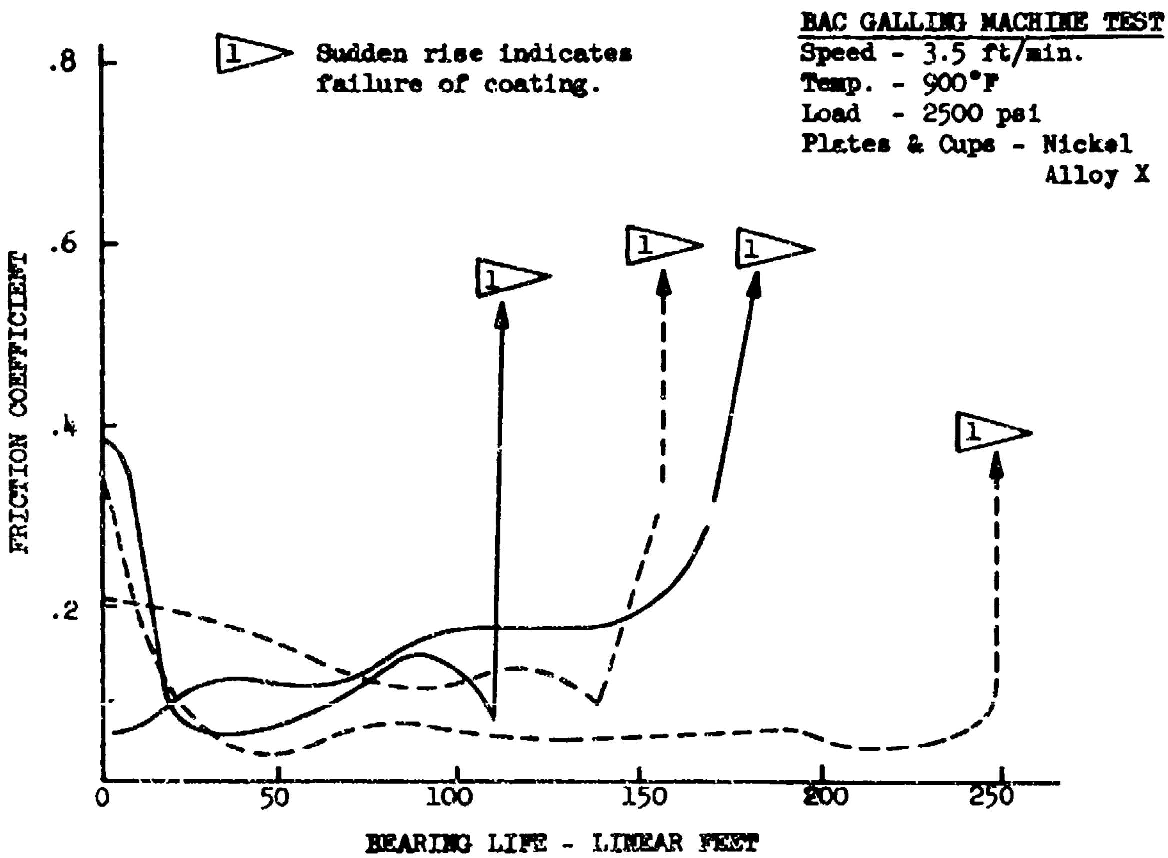


FIGURE 26 BOEING GALLING TESTS, FRICTION VS. LIFE CURVES, LOW SPEED

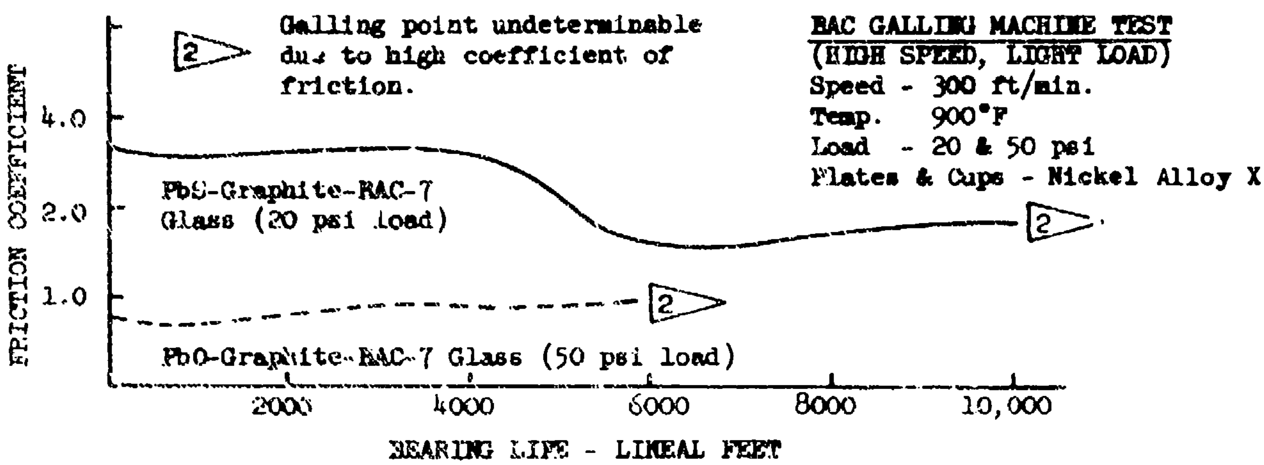


FIGURE 27 BOEING GALLING TESTS, FRICTION VS. LIFE CURVES, HIGH SPEED

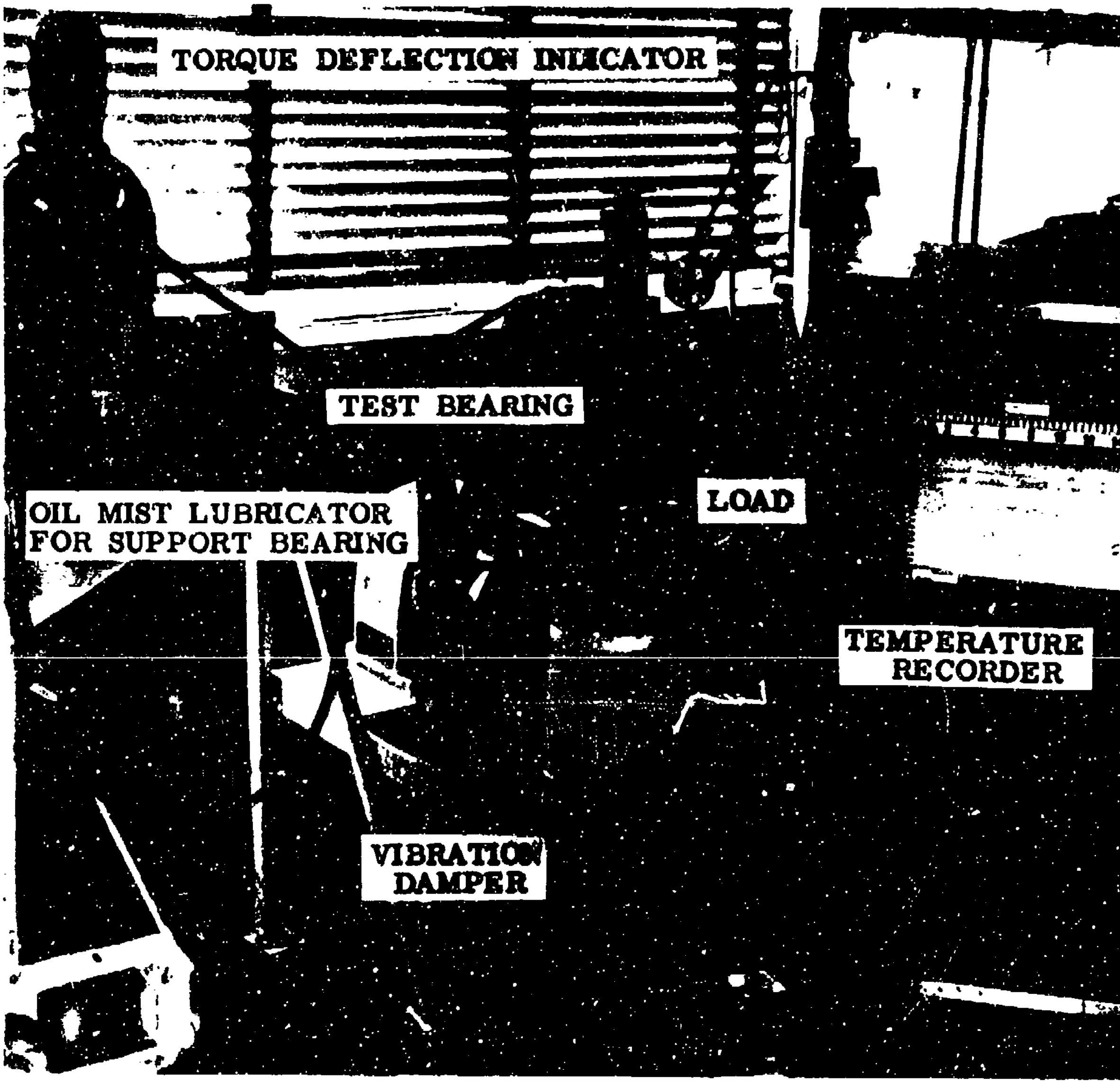


FIGURE 28 DRY FILM SCREENING TEST APPARATUS

Load was applied by applying 5 and 10 pound lead weights to the load arm to obtain various load requirements. The load was applied to the bearing housing through a yoke hinged at the shaft centerline. This method provided self-alignment for the straight bore plain bearings.

Coatings 1 through 5 and 9 through 12, previously listed, were evaluated on titanium carbide plain bushings and shafts at 3100 feet/min. in increasing load type screening tests on the high speed spindle. See Table VIII for results of these screening tests. Photographs of shafts and bearings after test are shown in Figures 29 and 30. The use of this screening test was discontinued because of the high cost of machining carbide shafts and bushings.

(4) 15,000 rpm 900°F Ball and Roller Bearing Tests

Lubricant coatings 4, 6, 7, 10 and 11 were applied to ball and roller bearings and evaluated on the 15,000 rpm, 900°F bearing test machine. Test results are listed in Tables II and III.

c. Methods of Lubricant Application

Various methods of lubricant applications were investigated and included the following:

(1) Spraying - Commercial solid lubricants and Boeing compounded ceramic type lubricants were applied in this manner.

(2) Flame Spraying - An attempt to apply lubricant coating No. 9 to titanium carbide cermet shafts and bushings did not prove feasible.

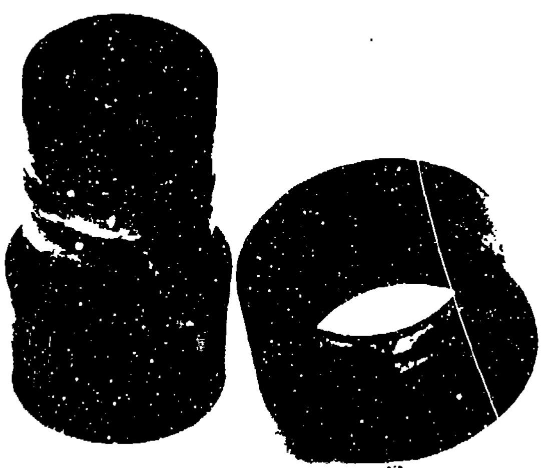
(3) Electrophoretic Deposition - This method involves the application of a lubricative material and binder out of a colloidal suspension by the use of an electrical current of very small amperage and relatively high voltages. Coatings 6, 7 and 8 were applied in this manner.

When all of the lubricant tests were analyzed and specimens examined it was found that none of the dry films tested had sufficient wear life.

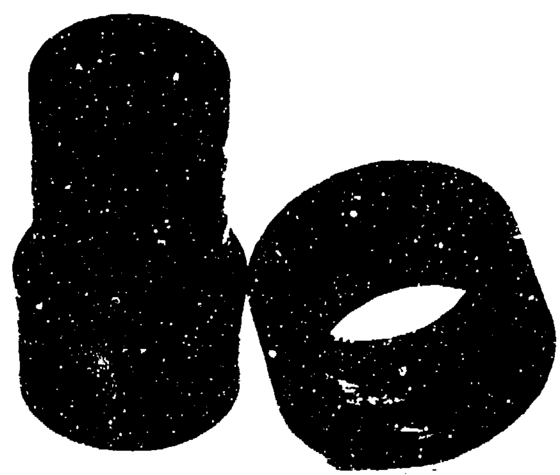
Accordingly a new approach to extend lubricant life was initiated. This approach uses a full complement bearing with rolling element spacers made from a lubricant composite material. Balls and rollers made from graphite and combinations of MoS_2 and Ni, 50%-50%, 70%-30%, 80%-20% and 90%-10%, have been fabricated. Data covering tests on graphite and on MoS_2-Ni 50%-50% are included in Table III of this report.

NO LUBRICATION
TEST #4

COATING 811
TEST #5

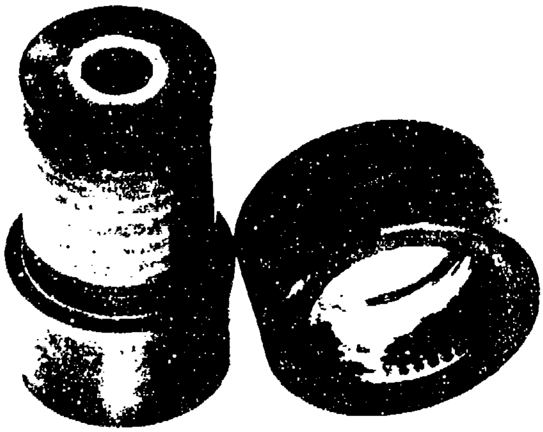


BAC-7 BINDER LEAD SULPHIDE
TEST #6

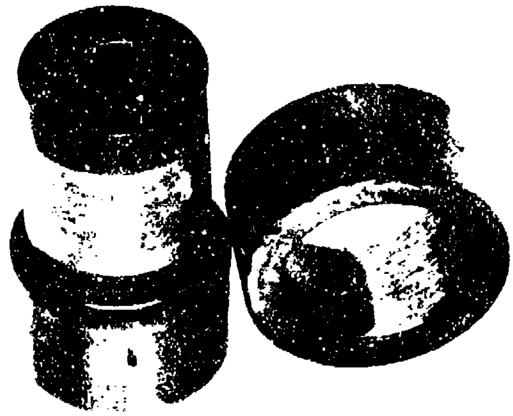


N.A.M.C.-23A DRY FILM
TEST #7

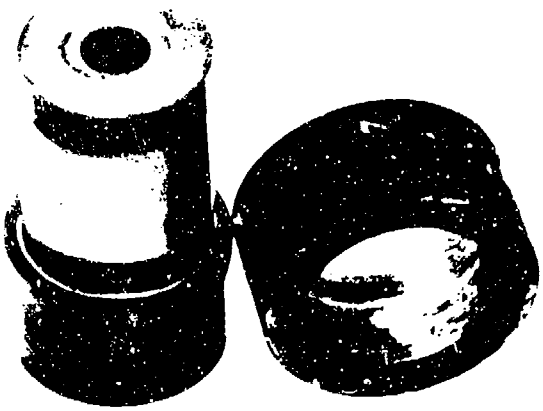
FIGURE 29 - SHAFTS AND BEARINGS AFTER TEST



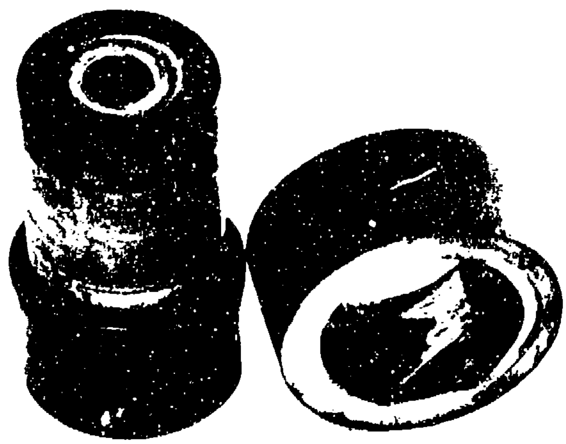
COATING M-1284
TEST #8



NO LUBRICATION
TEST #9



COATING M-1284
TEST #10



COATING 4396
TEST #11

FIGURE 30 - SHAFTS AND BEARINGS AFTER TEST

In order to determine the decomposition of titanium carbide K162B the powdered material was subjected to thermal gravimetric analysis and differential thermal analysis. The results of these analyses are shown on Figure 31.

Washington State University

During Phase I of this contract Washington State University obtained a 15,000 rpm 3100 feet/minute sliding friction machine for conducting screening tests. See Figure 32. This tester employs a simple reusable carbide stationary block which is pressed against a ring rotating at 3100 feet/minute. The rings are easily made from pressed rings of K162B and can also be remachined. The pressure between the block and the ring can be varied. Friction coefficient and temperature of the block are measured during the run.

The initial twelve runs made on the above machine used an increasing load procedure with inspection of the test block at 10 minute intervals. This procedure is outlined in Table XI. It was then decided that this procedure was too complex and time consuming. A simplified procedure was initiated in which a ten minute break-in period at a 4-pound load was followed by a 50 minute run at 20 pound load. No inspection of the test block was made until completion of the test. A detailed description of this procedure is shown in Table XII.

Coatings developed by Washington State University and The Boeing Company, as well as commercial lubricants, were subjected to screening tests on the equipment cited above.

A total of forty-eight screening tests were conducted. The values of friction coefficient, wear and temperature obtained in these tests are summarized in Tables XIII and XIV. Typical friction curves are shown in Figures 33 and 34. A photograph (Figure 35) illustrates wear scars on the test blocks.

In addition to the above tests, high speed ball bearing tests using 52100 steel bearings were conducted. The particular bearings used for these tests were 204K-01 bearings lubricated with phthalocyanine lubricant. It will be noted that the 52100 bearings were exposed to temperatures of 590°F for four hours in the phthalonitrile bath. This exposure would reduce the hardness of the bearing elements considerably. Test results are included in Table IX.

Development work was initiated on the phthalocyanine coatings and the phosphonitrilic chloride polymers.

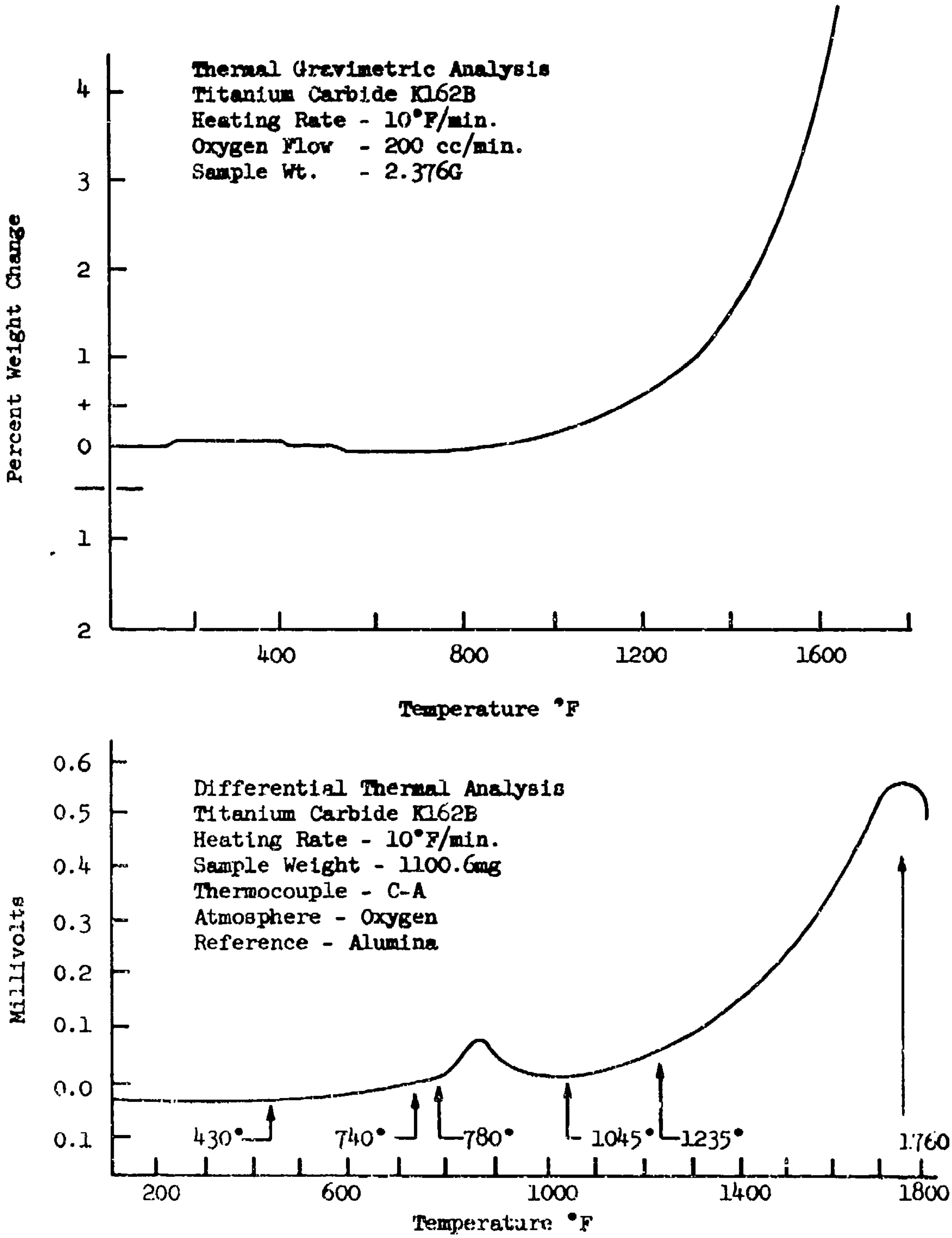


FIGURE 31 THERMAL GRAVIMETRIC ANALYSIS OF K162B

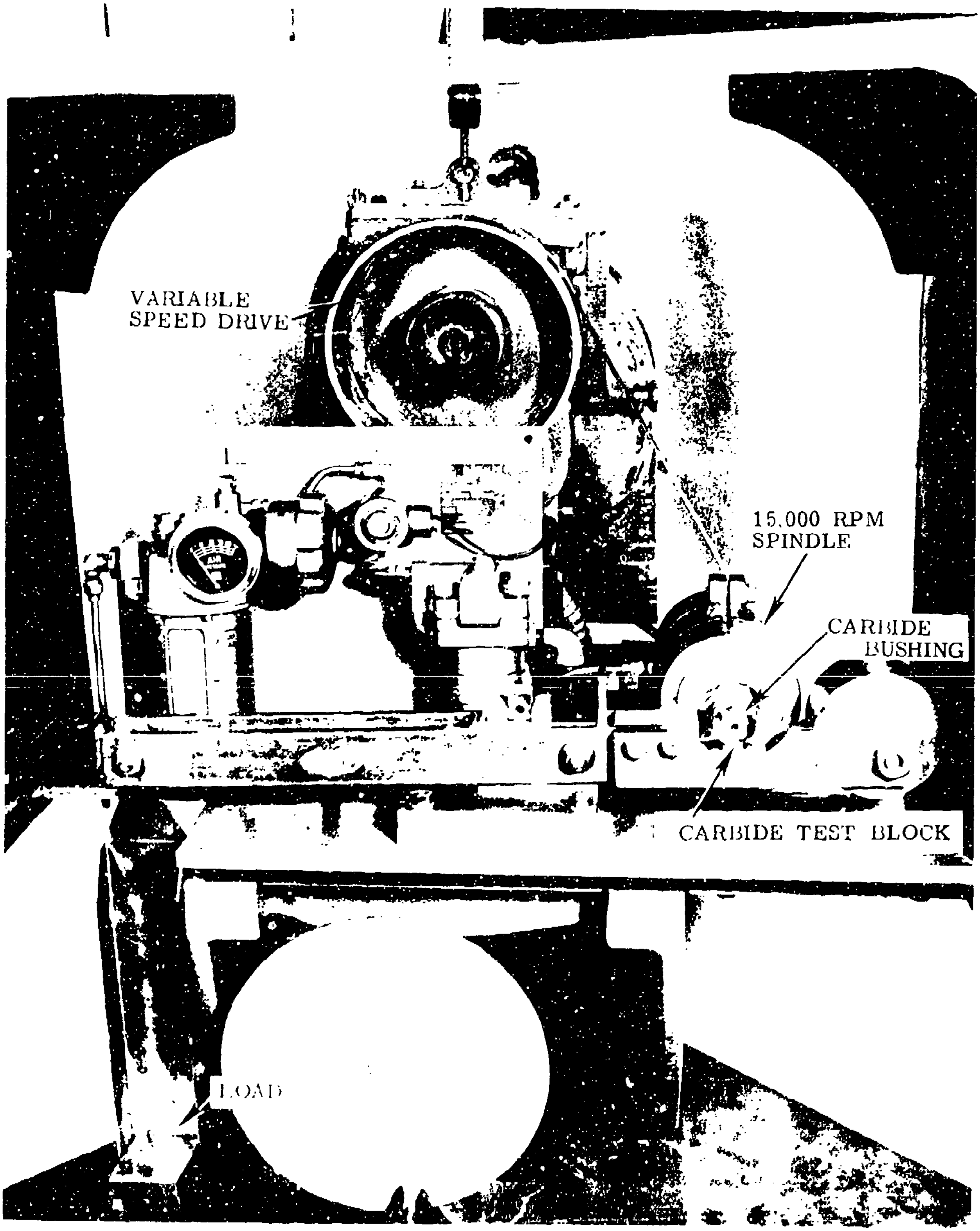


FIGURE 3 2 WASHINGTON STATE UNIVERSITY TESTER

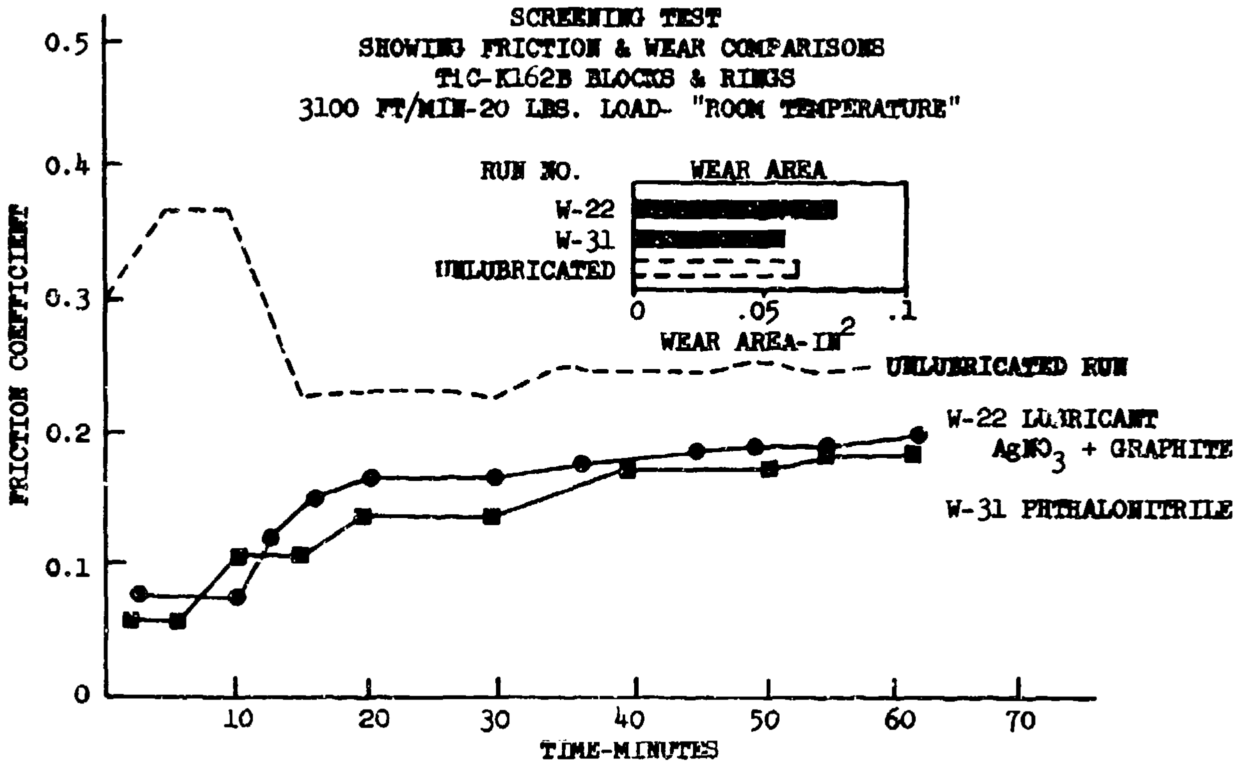


FIGURE 33 SCREENING TEST LUBRICANT COMPARISON

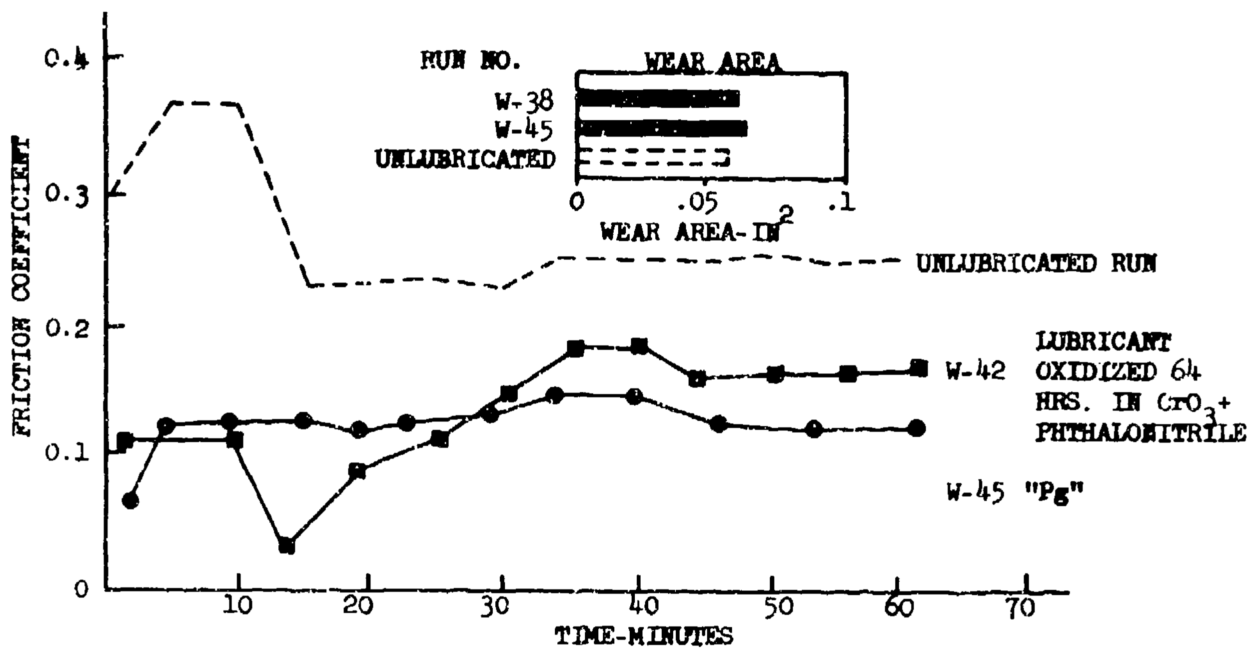


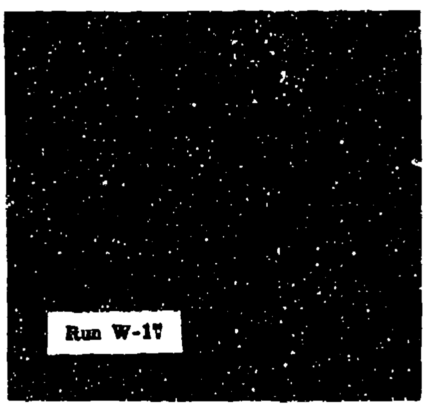
FIGURE 34 SCREENING TEST LUBRICANT COMPARISON

No lubricant.
Scar area = .0570 in^2.

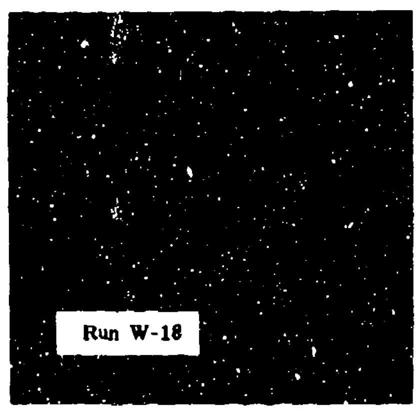
No lubricant.
Scar area = .0588 in^2.

No lubricant
Scar area = .0565 in^2.

Lubricant - 1284 (Coated by Boeing)
Scar area = .0811 in^2.



Lubricant - B.A.C. Ceramic Dry Film
(coated by Boeing)
Scar area = .0637 in^2.



Lubricant - phthalonitrile bath with
specimens oxidized at 1000°F
Scar area = .0490 in^2.

FIGURE 35 WEAR OF CARBIDE TEST BLOCKS

An orthophthalonitrile bath was set up to coat titanium carbide specimens. Parts were immersed in this bath for several hours at 590°F to produce a chelated phthalocyanine coating.

In an effort to produce heavier more wear resistant phthalocyanine lubricant coatings a program of oxidation pretreatments for titanium carbide was initiated.

Oxidation pretreatments for titanium carbide included the following:

(a) Exposure for periods of up to 24 hours at 1000°F in air.

(b) Immersion in concentrated HNO_3 room temperature.

(c) Immersion in boiling NaOH 20%.

(d) Immersion in concentrated CrO_3 for 24 hours at room temperature.

(e) Immersion in concentrated CrO_3 for 64 hours at room temperature.

(f) Immersion in concentrated $KMnO_4$ for 64 hours at room temperature.

(g) Immersion in concentrated $(NH_4)_2C_2O_4 \cdot H_2O$ for 17 hours, boiled for four hours.

(h) Exposure to temperatures up to 2200°F for four hours max.

3. DISCUSSION OF RESULTS

The Boeing Company

a. Dry film screening tests using titanium carbide shafts and bushings demonstrated that M-1284 (see Table VIII) was the best dry film tested. However, it is not felt that the results from this test were conclusive due to (1) the dependence of the results of mechanical factors such as the bushing shaft clearance and (2) cracking of the bushings which terminated some of the test runs prematurely.

b. A plain bearing was run in the bearing test machine for 17 hours in air at 900°F using a phthalocyanine lubricant coating. The change in dimension of the thrust face of the bearing (0.014 inch) indicated that the coating had completely worn off. The continuing low friction level would indicate that the carbide surface was to some degree self lubricating. The friction coefficient during the run decreased from an initial value of .30 to .25 at 17 hours. After the run, a yellow powder type substance covered the bearing housing and bearing. X-ray diffraction and spectrographic analysis established that this material was mainly a combination of rutile (TiO_2) and nickel oxide (NiO) in the ratio of 2 to 1. This material was evidently formed by the oxidation of the carbide and acted as a lubricant.

c. The results of one test in vacuum at 10^{-6}mm Hg, Table I, indicate that phthalocyanine is not a good lubricant for a vacuum system. Therefore it was not considered for future tests.

d. Results of tests using lubricant composite spacer rollers, Table III, appear promising. This approach was investigated at greater length during Phase II at 1500°F.

Washington State University

Test results of all screening tests are included as Tables XIII and XIV. All lubricants tested on the Washington State University screening tests appeared to be inferior to the phthalocyanine lubricant except "Pg". (See Figures 33 and 34).

Of the oxidation pretreatments investigated at Washington State University, the 4 hours at 1000°F in air and those in CrO_3 appeared to be the most promising.

The method of applying phthalocyanine lubricant coating at Washington State University was satisfactory. However, this material is very limited relative to heat resistance and therefore was not used in further tests over 900°F.

The lubricant film screening test machine constructed by Washington State University showed a high degree of correlation with the Boeing bearing test machine.

[illegible]

[illegible]

TEST NO.	TYPE OF DRY FILM	COATING THICKNESS SHAFT INCHES	COATING THICKNESS BUSHING INCHES	INITIAL RADIAL PLAY	TOTAL WEAR INCHES	BEARING LIFE IN MINUTES	MAX. TEMP. REACHED	MAX. STRESS PSI	REMARKS
[illegible]		------	------	[illegible]	------	31			Failure: Preliminary test*. Seizure imminent.
[illegible]		[illegible]	[illegible]	[illegible]	.0032	50	1050°F	164.0	Failure: Cracked bearing.
[illegible]	None	------	------	.0012	.0013	25	625°F	63.6	Sleeve cracked at 9 min., 40 sec. Test continued. Failure: Seizure.
4	None	------	------	.0019	------	41	900°F	164.0	Wear not measurable due to bearing seizure.
5		.0015	.0001	.0015	.0004	31	775°F	88.0	Failure: Seizure.
[illegible]	[illegible]	.0015	.00045	.0016	.0004	31	640°F	88.0	Failure: Seizure.
[illegible]	[illegible]	.0015	.0001	.0017	.0007	42	950°F	164.0	Failure: Crack in bearing.
[illegible]	[illegible]	.0001	.0002	.0029	.0051	80	1150°F	164.0	Ran 50 min. screening test and 30 min life test. Failure: Wear exceeds .005 in. and cracked bearing.
[illegible]	None	------	------	.0031	.0019	50	1100°F	164.0	Failure: Cracked bearing.
[illegible]	[illegible]	.0015	.0003	[illegible]	.0025	41	750°F	164.0	Failure: Seizure.
[illegible]	[illegible]	.0002	.0002	.0034	.0029	50	1225°F	164.0	Failure: Seizure.
[illegible]	[illegible]	[illegible]	.0004	.0050	.0030	50	1150°F	164.0	Failure. Cracked bearing.
[illegible]	[illegible]	.0006	.0003	.0029	.0054	50	1000°F	164.0	Failure. Cracked bearing.
[illegible]		[illegible]	.0015	.004	.0032	50	1175°F	164.0	Failure. Cracked bearing.

* [illegible] test only. In all other tests a titanium carbide cermet, K-162B, was the shaft and bearing material.

TABLE IX

WASHINGTON STATE UNIVERSITY HIGH SPEED BALL BEARING TEST

RUN NO.	PREPARATION	MAXIMUM RPM	INITIAL CLEARANCE	TEMPERATURE AT OUTER RACE	LOAD IN LBS.	RUN TIME MAXIMUM RPM	REMARKS
B-1	None	3,600	0.00012	*	10	4 hours	Retainer failed.
B-2	Metal-free Phthalocyanine	3,600	0.00039	*	10	6 hours	Bearing in excellent condition.
B-3	PbO	3,600	0.00052	*	10	6 hours	Bearing in excellent condition.
B-4	4% metal-free Phthalocyanine, 4% nom 38 graphite, 92% Hypo Phosphoric acid.	3,600	0.0007	*	10	6 hours	Excessive wear.
B-5	30% PbO, 30% acheson no. 38 Graphite, 10% Polyisobutylene	3,600	0.00058	*	10	50 hours	No failure - Extremely long life of lubricant.
B-6	Bearing cleaned, then lubricated with 100% Phthalonitrile. Bearing and lubricant prefired at 590°F for 4 hours in Polyisobutene bath.	3,600	.0001 in	*	75	40 hours	Ball retainer shattered into small pieces.
B-7	Prepared identically the same as the bearing for run B-6.	15,000	.0007 in.	165°F	75	4.5 min.	Section of retainer covering one ball failed.
B-8	Bearing cleaned, then run unlubricated	15,000	.0008 in.	125°F	75	2.2 min.	Retainer failed.
B-9	Bearing cleaned, then run unlubricated.	15,000	.0004 in.	150°F	75	1.5 min.	Bearing froze, stalling motor.
B-10	Given same treatment as B-6 and B-7.	15,000	.00047 in.	375°F	25	9 min.	Retainer failed.

*Outer race temperature not measured in initial tests.

NOTE: Specimens used on tests 1 thru 9 were 204K-01 52100 steel bearings.

TABLE X

FORMULATION OF DRY FILM LUBRICANTS

DRY FILM	LUBRICANT, WT. %		BINDER, WT. %		PREPARATION	CURE
NAMC-AML	Graphite	3.8%	Sodium Silicate Solution K Water	 26.8% 32.0%	Mix dry lubricants and slowly add water and sodium silicate. Stir well.	Air Dry 180°F - 24 hours 300°F - 24 hours
BAC-7-Lead Sulphide	PbS Graphite	25% 25%	BAC-7 Glass binder (proprietary)-50%		Ball mill for 12 hours in isopropanol and spray.	10 minutes at 1050°F
Boric Oxide-PbS	PbS	50%	Boric Oxide as H_3BO_3	50%	Ball mill 12 hours in water. Dilute with water and spray.	10 minutes at 1100°F. Pre-heat furnace.
Bi_2O_3 -silver BAC 8	Bi_2O_3 Ag	25% 25%	Bu Standards A-418 ceramic adhesive. NBS Frit no. 332	50%	Ball mill 12 hours in isopropanol. Dilute with isopropanol and spray	10 minutes at 1850°F.
Dry film coating	MoS_2 PbS	30.8% 62.5%	Boric Oxide as H_3BO_3	7.7%	Ball mill for 12 hours in 70% isopropanol, 30% water. Dilute with isopropanol and spray.	Cure at 1150°F for 1 hour in N_2 atmosphere.
CaF_2*	CaF_2	75%	Bu Standards A-14 ceramic adhesives NBS Frit no. 332	25%	Ball mill 12 hours in isopropnalo applied by Electrophoretic deposition.	10 minutes at 1850°F

*Coatings caused excessive pitting of TIC test specimens.

TABLE X CONT.

FORMULATION OF DRY FILM LUBRICANTS

DRY FILM	LUBRICANT, WT. %		BINDER, WT. %		PREPARATION	CURE
PbO	PbO	75%	Bu Standards A-418 ceramic adhesive NBS Frit no. 322	25%	Ball mill 4 hours in acetone applied by electrophoretic deposition	30 minutes at 1500°F
Dry film coating	MoS_2 PbS	61.6 30.8	Boric Oxide as H_3BO_3	7.6%	Ball mill for 12 hours in 70% isopropanol 30% water. Applied by spray gun	1150°F for one hour in inert atmosphere
CaF_2 + Silver*	CaF_2 Ag	50% 25%	Bu Standards A-418 adhesive NBS no. 332	25%	Ball mill for 4 hours in isopropanol applied by electrophoretce deposition	10 minutes at 1850°F

*Coatings caused excessive pitting of TIC test specimens.

TABLE XI

TEST PROCEDURE WASHINGTON STATE UNIVERSITY LOAD SPECTRUM TEST

A. Temperature – Induced by Friction

B. Load

1. 1 pound for 10 minutes
2. 4 pounds for 10 minutes
3. 8 pounds for 10 minutes
4. 16 pounds for 10 minutes
5. 20 pounds for 20 minutes

C. Test to be stopped at each 10 minute interval, wear scar area of block measured and parts inspected. The exception here is the 20 minute interval without stopping at the 20 pound load.

D. The following data is taken during the test:

1. Friction coefficient (by use of a strain gauge and recorded by a Brush analyzer).
2. Bearing temperature, °F.
3. Speed, feet/minute (not recorded but kept constant).
4. Load, lbs.
5. Wear scar area, $in.^2$ at each ten minute interval.
6. Time, minutes.

TABLE XII

TEST PROCEDURE WASHINGTON STATE UNIVERSITY 20 POUND LIFE TEST

A. Temperature - Induced by Friction

B. Load

1. Break in period at 4 pound load for 10 minutes.

2. Load increased from 4 pound to 20 pound over a time interval of 1 minute.

3. Test continued at the 20 pound load for 49 minutes, making the total run time 60 minutes.

C. Duration - Test run continuously over the 60 minute period with the speed maintained at 3,100 feet/minute.

D. Data Taken During Test

1. Friction coefficient (by use of a strain gauge and recorded by a Brush analyzer).

2. Bearing temperature, °F.

3. Speed, feet/minute (not recorded but kept constant).

4. Load, lbs.

5. Time, minutes.

E. Data Taken After Completion of Test - Wear scar area in square inches.

TABLE XIII

WASHINGTON STATE UNIVERSITY HIGH SPEED FRICTION TEST, INCREASING LOAD

RUN NO.	LUBRICANT NO. & PREPARATION	MAXIMUM TEMP. °F	FINAL SCAR AREA, IN.^{2}	COEFFICIENT OF FRICTION MIN.	MAX.	REMARKS
W-1	Unlubricated	300 at 20 lbs.	.0381	.125 at 20 lbs.	1.5 at 1 lbs.	Slight striation.
W-2	Unlubricated (Duplicate of W-1)	340 at 20 lbs.	.0517	.225 at 20 lbs.	1.5 at 1 lbs.	Slight striation.
W-3	Unlubricated (Duplicate of W-1 & W-2)	340 at 20 lbs.	.0492	.175 at 20 lbs.	1.00 at 1 lb.	Slight striation.
W-4	W-4. Specimens maintained at 590°F for 4 hours, in phthalonitrile bath. Some of reaction mixture rubbed onto specimen surfaces prior to test.	270 at 20 lbs.	.0311	.094 at 16 lbs.	.500 at 1 lb.	Smooth, fine striation.
W-5	W-5: Same as above (Duplicate of W-4)	310 at 20 lbs.	.0233	.125 at 16 lbs.	.750 at 16 lbs.	Smooth, fine striation.
W-6	W-6: Placed in $(PNCl_2)_3$ and $(PNCl_2)_4$ bath for 2 hours at 400°F, then additional $(PNCl_2)_3$ and $(PNCL_2)_4$ rubbed onto specimen surfaces.	370 at 20 lbs.	.0577	.225 at 20 lbs.	1.000 at 1 lb.	Striated.
W-7*	W-7: (a) Ring & Block oxidized at 1000°F for 4 hours. (b) Oxidized specimens then placed in an orthophalonitrile orthophalonitrile bath maintained at 590°F for 4 hours.	210 at 20 lbs.	.0166	.05 at 20 lbs.	.750 at 1 lb.	No striation or galling.
W-8*	W-8: 60% $(PNCL_2)_3$ and $(PNCL_2)_4$, 50% $SbCl_3$. Treated 2 hours at 400°F.	350 at 20 lbs.	.0432	.125 at 4 & lbs.	.500 at 1 lb.	Rubbery polymer formed after firing. Heavy wear & striation occurred at 16 and 20 lb. loads.
W-9	W-9: 50% $(PNCL_2)_3$, 50% Acheson 38 Graphite. Treated 2 hours at 400°F.	300 at 20 lbs.	.0333	.225 at 20 lbs.	.750 at 1 lb.	No adherence of lubricant to specimen.
W-10	W-10: (a) Block and Ring oxidized at 1000°F for 4 hours. (b) Specimens then placed in 80% phthalonitrile + 20% Acheson 38 Graphite bath and maintained at 590°F for 4 hours.	280 at 20 lbs.	.0411	.156 at 16 lbs.	1.000 at 1 lb.	Scar area even, slight striation.
W-11	W-11: Specimens covered with Heliogen Blue BG (M-F Phthalocyanine) and maintained at 1000°F for 48 hours under a nitrogen atmosphere.	330 at 20 lbs.	.0517	.175 at 20 lbs.	.500 at 1 lb.	Only slight phthalocyanine film formed on specimen surfaces. Scar area large.
W-12	W-12: (a) Specimens oxidized at 1500°F for 4 hours. (b) Specimens then placed in phthalonitrile bath maintained at 590°F for 4 hours.	320 at 20 lbs.	.0404	.125 at 4 & 8 lbs.	.250 at 20 lbs.	The lubricant appeared to have worn through during the 8 lb. load at which time increased friction and wear began.

* Additional lubricant added during test.

TABLE XIV

WASHINGTON STATE UNIVERSITY HIGH-SPEED FRICTION TESTS, CONSTANT LOAD

MATERIAL: K-162B
SPEED: 3100 FT MIN.

RUN NO.	LUBRICANT NO. AND PREPARATION	MAXIMUM TEMP. °F	FINAL SCAR AREA, IN.^{2}	COEFFICIENT OF FRICTION MIN.	COEFFICIENT OF FRICTION MAX.	REMARKS	TIME COEFFICIENT OF FRICTION REMAINED BELOW 0.20
W-13	Unlubricated	340	.0570	.250 at 20 lbs.	.438 at 4 lbs.	Slight striation on ring and block	-0-
W-14	Unlubricated (Duplicate of W-13)	370	.0588	.225 at 20 lbs.	.312 at 4 lbs.	Slight striation on ring and blocks	-0-
W-15	Unlubricated (Duplicate of W-13 and W-14)	360	.0565	.200 at 20 lbs.	.375 at 4 lbs.	Slight striation on ring and blocks	-0-
W-16	W-16. 1284 coated by B.A.C.	420	.0811	.300 at 20 lbs	.500 at 4 lbs.	Excessive scar area on block. Ring not galled.	-0-
W-17	W-17: B.A.C. Ceramic dry film coated by B.A.C.	350	.0537	.187 at 4 & 20 lbs.	.275 at 20 lbs.	Coating appears to have worn through. Slight striation.	8 minutes
W-18	W-18: (1) Specimens oxidized at 1000°F for 4 hours. (2) Oxidized specimens immersed in phthalonitrile at 590°F for 4 hours.	300	.0490	.0875 at 20 lbs.	.225 at 20 lbs.	Ring smooth. Coating appears to be worn through however, no galling or striation evident.	25 minutes
W-19	W-19: 20% Ach. 38 Graphite, 20% Orthophthalonitrile, 60% AgCl. Fired 6 hours at 1000°F (lube applied twice).	360	.0821	.250 at 20 lbs.	.500 at 4 lbs.	Friction and wear high.	-0-
W-20	W-20: (1) Specimens oxidized for 4 hours at 1000°F. (2) Oxidized specimens immersed in orthophthalonitrile bath maintained at 590°F for 4 hours. (3) Steps 1 & 2 repeated twice.	320	.0682	.150 at 20 min	.200 at 60 min.	Coating not improved.	-0-
W-21	W-4: Specimens immersed in orthophthalonitrile and maintained at 590°F for 4 hours.	320	.0632	.125 at 2 min.	.275 at 50 min.	Lubricant life short.	5 min.
W-22	W-22: 20% Ach. 38 Graphite 80% $AgNO_3$. Fired 1 hr at 800°F.	320	.0728	.0625 at 0-10 min.	.212 at 60 min.	Wear high, initial friction low.	13 minutes
W-23	W-23: 15% Ach. 38 Graphite, 70% $AgNO_3$, 15% Orthophthalonitrile. Fired 1 hour at 800°F.	340	.0854	.150 at 12 min.	.250 at 10 & 45 min.	Wear and friction high. No striation.	-0-
W-24	W-24: (1) Specimens oxidized at 1000°F for 8 hours. (2) Oxidized specimens immersed in orthophthalonitrile for 4 hours at 590°F.	320	.0645	.125 at 2 min.	.200 at 30-60 min.	No galling or striation.	5 minutes
W-25	W-25: 80% $AgNO_3$, 20% Ach. 38 Graphite (1) Applied in slurry of poly phenyl ether. (2) Fired 1 hr. at 800°F (3) Specimens coated with poly phenyl ether prior to start of test.	350	.0588	.0625 at 2 min.	.250 at [illegible]-60 min.	Wear reduced, no striation or galling.	14 minutes
W-26	W-26: (1) Specimens oxidized at 1[illegible]0°F for 24 hours. (2) Oxidized specimens immersed in orthophthalonitrile at 590°F for 4 hrs.	330	.0603	.125 at 2 min.	.188 at 10 min.	Ring and block in excellent condition.	7 minutes
W-27	W-27: (1) Specimens oxidized for 4 hours at 1000°F (2) 80% $AgNO_3$, 20% Ach. 38 Graphite. Fired 1 hour at 800°F.	310	.0650	.175 at 15 min.	.312 at 0-10 min.	Slight striation	-0-
W-28	Unlubricated	370	.0696	.187 at 15 min.	.250 at 0-10 and 40-60 min.	Striation on ring and block.	-0-
W-29	W-29: Duplicate of run W-26. (1) Specimens oxidized at 1000°F for 24 hours. (2) Oxidized specimens immersed in orthophthalonitrile at 590°F for 4 hours.	300	.0639	.063 at 0-5 min.	.175 at 50-60 min.	Ring and block in excellent condition.	12 minutes
W-30	Unlubricated (Duplicate of run W-28)	380	.0710	.162 at 12-20 min.	.313 at 10 min.	Striation on ring and block.	-0-
W-31	W-7: (1) Specimens oxidized for 4 hrs. at 1000°F (2) Oxidized specimens immersed in orthophthalonitrile at 590°F for 4 hours.	370	[illegible]	.0625 at 0-5 min.	.187 at 55-60 min.	Wear scar area reduced.	17 minutes.
W-32	W-4: (1) Specimens sand blasted. (2) Specimens immersed in orthophthalonitrile at 590°F for 4 hours.	310	.0590	.125 at 12 min.	.187 at 0-10 min.	Wear scar on block reduced.	4 minutes

TABLE XIV CONTINUED

RUN NO.	LUBRICANT NO. AND PREPARATION	MAXIMUM TEMP., °F	FINAL SCAR AREA, IN.²	COEFFICIENT OF FRICTION MIN.	COEFFICIENT OF FRICTION MAX.	REMARKS	TIME COEFFICIENT OF FRICTION REMAINED BELOW 0.20
W-33	W-33: (1) Specimens sand blasted. (2) Specimens oxidized 4 hrs. at 1000°F. (3) Oxidized specimens immersed in orthophthalonitrile at 590°F for 4 hours.	330	.0555	.100 at 12 min.	.162 at 20 min	Wear scar on block reduced.	27 minutes
W-34	W-34: 100% metal free phthalocyanine, rubbed on by hand.	300	.0620	.0875 at 12 min.	.187 at 0-10 & 40-60 min.	Lubricant applied heavily at start of test.	11 minutes
W-35	W-35: (1) Specimens pickled in Conc. HNO_3. (2) Pickled specimens oxidized at 1000°F for 4 hours. (3) Oxidized specimens immersed in orthophthalonitrile at 590°F for 4 hours.	380	.0716	.175 at 12 min.	.250 at 0-10 min.	Surface uneven from HNO_3 etch. Friction and wear high.	-0-
W-36	W-36: Oxidized at 1000°F for 4 hours.	280	.0621	.150 at 12 min.	.250 at 5-10 min.	Slight striation on specimen surface.	-0-
W-37	W-37: (1) Specimens boiled in 20% NaOH solution for 2 hours. (2) Specimens immersed in orthophthalonitrile at 590°F for 4 hrs.	380	.0600	.162 at 12 min.	.212 at 55-60 min.	Slight striation on specimen surfaces.	-0-
W-38	W-38: (1) Specimens oxidized in Conc. CrO_3 at room temp. for 24 hours. (2) Specimens immersed in orthophthalonitrile at 590°F for 4 hours.	360	.0629	.0875 at 55-60 min.	.187 at 5-10 min.	Specimen surfaces smooth.	54 minutes
W-39	W-39: (1) Oxidized at 1000°F for 4 hours. (2) Immersed in 50-50 cupferron-orthophthalonitrile mixture at 590°F for 4 hours.	290	.0652	.175 at 15 and 55-60 min.	.250 at 0-10 min.	Slight striation on specimen surfaces.	-0-
W-40	W-40: (1) Oxidized at 2200°F for 4 hours. (2) Immersed in orthophthalonitrile at 590°F for 4 hours.	440	.123	.275 at 25-30 min.	.375 at 0-10 min.	Specimens deformed and surfaces severely oxidized. Friction, wear & temperature very high.	-0-
W-41	W-41: (1) Specimens oxidized with CrO_3 at 2200°F for 4 hours. (2) Oxidized specimens immersed in an orthophthalonitrile bath maintained at 590°F for 4 hours.	630	.120	.125 at 0-5 min. Recorder broke down after 20 minutes of test had been completed.	.187 at 10 min.	Specimen surfaces severely oxidized. Frictional temperature was extremely high - the contact surface being red-hot.	-0-
W-42	W-42: (Duplicate of W-38) (1) Specimens oxidized in Conc. CrO_3 solution for 64 hours at room temperature. (2) Immersed in orthophthalonitrile at 590°F for 4 hours.	320	.0412	.0375 at 12 min.	.175 at 35-40 min.	Specimen surfaces smooth.	45 minutes
W-43	W-43: (1) Oxidized in Conc. $KMnO_4$ for 64 hours, at room temperature. (2) Immersed in orthophthalonitrile at 590°F for 4 hours.	350	.0495	.075 at 12 min.	.150 at 20 min.	Recorder broke down after 30 minutes of test.	
W-44	G-805	430	.0784	.0625 at 2 min.	.250 at 12 min.	Striated.	10 minutes
W-45	Pg	240	.0672	.0625 at 2 min.	.137 at 3-30 min.	Slight striation, no galling.	60 minutes
W-46	W-46. (1) Specimens placed in Conc. $(NH_4)_2C_2O_4 \cdot H_2O$ for 17 hours at room temperature, then boiled for 4 hours. (2) Immersed in orthophthalonitrile at 590°F for 4 hours.	300	.0628	.125 at 5 min.	.187 at 5-10 min.	Slight striation.	2 minutes
W-47	W-47: 100% LIF maintained at 1200°F for 1 hour.	370	.0603	.150 at 12-60 min.	.187 at 0-12 min.	Surface of ring was pitted.	-0-
W-48	W-48: (1) 100% LIF maintained at 1200°F for 1 hour. (2) Immersed in orthophthalonitrile at 590°F for 4 hours.	370	.0579	.100 at 12 min.	.187 at 50-60 min.	Surface of ring was pitted	6 minutes

PHASE II LUBRICANT DEVELOPMENT

1. INTRODUCTION

The thin films of solid lubricants tested during Phase I were not satisfactory for operation under the conditions required for bearing performance in Phase II of this contract. Therefore, lubricant development work for Phase II was directed toward the use of lubricant composite materials described in the Phase I Materials Section, Lubricant Development on pages 77 & 86 of this report. Various changes and redirections of the Phase II portion of the contract are described on pages 39 and 40 of this report. During Phase II all of the lubricant development was done in the Boeing laboratories. A supplementary testing program was conducted at Washington State University.

2. LUBRICANT DEVELOPMENT

a. The Boeing Company

Dry-Pressing

The initial investigation into the development and fabrication of lubricant composite materials consisted of a series of dry pressing tests at room temperature. These tests were accomplished by compacting molybdenum disulfide powder under various loads from 3080 psi to 185,000 psi. Neither MoS_2, nor mixtures of MoS_2 and binders, nor the substitution of other materials for MoS_2 produced lubricant composites with fracture strengths equal to or exceeding the 460-pound fracture strength of the base line material, ATJ graphite (see below). Data covering forty-one dry-pressing tests are included as Tables XV and XVII.

Fracture Tests

To provide some rapid preliminary method of screening the lubricant composite materials, a procedure was established for determining their fracture strength. This was accomplished by placing a short piece of the composite in the "V" of a standard Falex "V" block and applying a compression load with a Tinius-Olsen Tensile Machine. This procedure was later revised and a Brown and Sharpe "V" block No. 750A was substituted for the Falex "V" block. Fracture tests were conducted on all fabricated specimens. Data covering fracture tests are included in Tables XV, XVI and XVII. Phase I bearing tests showed that ATJ graphite had sufficient strength to be used for spacer-rolling elements. Therefore, ATJ graphite was considered as the base line material. The fracture strength of ATJ graphite was found to be 460 pounds when tested as described above. In all following work, attempts were made to produce lubricant composites equal to or better than ATJ graphite in fracture strength.

Exposure Tests

A minor screening test employed during part of the Phase II program involved subjecting the finished lubricant composites to exposure in a vacuum at 1500°F. The vacuum system used produced a vacuum of only 25 microns; consequently, some of the composites suffered from slight oxidation.

Friction and Wear Tests

A supplemental screening test for the determination of friction and wear characteristics of the lubricant composites was conducted on a complementary Boeing sponsored effort. In this test, lubricant composite specimens were loaded against a rotating K162B titanium carbide ring at a surface speed of 7000 ft/min. Tests were run for a period of ten minutes under light load (5 lbs.) at room temperature. Data covering results of the 66 tests conducted are included as Table XX.

Hot Pressing

Since dry-pressing did not produce the required 460-pound fracture strength desired, efforts were directed toward hot-pressing. Dies 3-1/2 inches square and five inches long were made of ATJ graphite. (See Figure 36). A hole was drilled the length of each die to provide a die cavity. Considerable difficulty was encountered with the original set of dies. This was overcome by careful reaming of the die cavity. Final sizing of the pressed blanks was accomplished by grinding.

Lubricant composites were fabricated by: (1) heating mixtures of lubricants and metallic or inorganic binders in a vacuum furnace to 350°F to drive off water vapor, (2) mixing thoroughly, (3) pressing the lubricant materials at room temperature in the graphite dies to insure sufficient material to fabricate the necessary numbers of rollers, (4) preheating the dies to 1200°F, (5) hot-pressing at temperatures of from 1600 to 2500°F, (6) cooling under load to 1400°F, (7) cooling without load from 1400°F to 500°F and (8) pressing the lubricant composite from the die. Some variations to the above process have been used and are noted in Table XVI. Table XVI lists all of the lubricant composite specimens as well as duplicate and formulated but not fabricated specimens.

Thermal Expansion Measurements

Bearing test failures cited in Table IV were attributed to the dimensional instability of the lubricant composite spacer rolling elements. Therefore, a series of linear thermal expansion measurements were conducted to determine the amount of dimensional change.

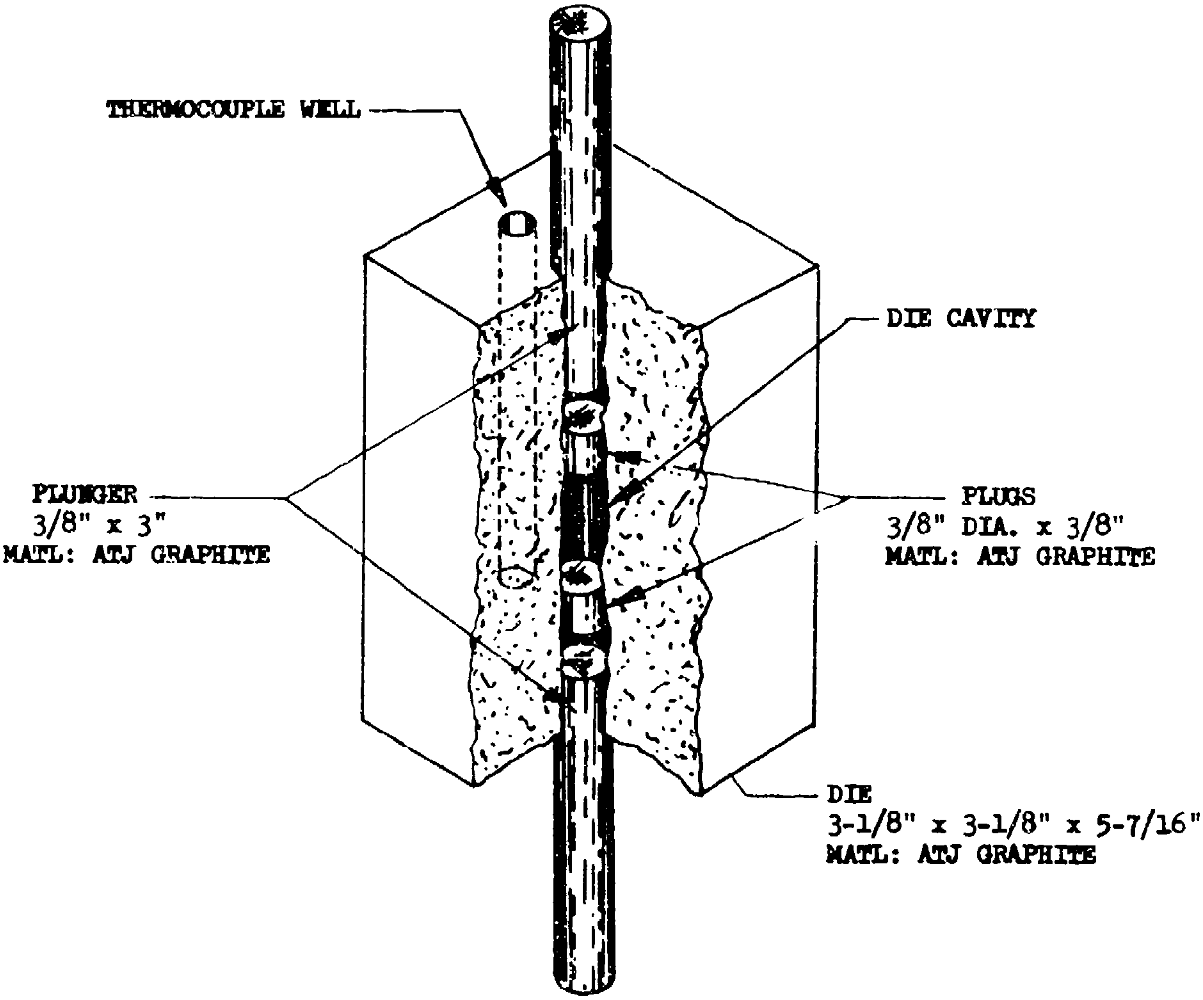


FIGURE 36 GRAPHITE DIE

Measurements were made on the titanium carbide K162B bearing material, and on hot-pressed compacts of MoS_2 with 0, 10 and 15% nickel binders. The specimens used were 0.420- to 0.500-inch diameter cylinders 1 to 2 inches in length. They were heated in a quartz dilatometer to 850°C (1562°F) in a 99.996% pure argon atmosphere. Measurements were obtained at 100°C increments during the heating and cooling cycles. The heating and cooling rates were maintained between 2 and 3°C per minute. Below 300°C the rate of cooling decreased because of the low heat loss of the furnace.

Initial measurements made on the K162B carbide material (Figure 37) correlate within 1% to the thermal expansion measurements made by the National Bureau of Standards Report No. 1503.

The hot-pressed MoS_2 compact No. 212 (Figure 38) exhibited a significant dimensional instability above 600°C in the initial measurement. The specimen was maintained at 850°C for 20 hours before stability was noted. An increase in specimen length of 0.020-inch was measured after test. It was considered that the 20-hour soak at 850°C should have significantly eliminated the dimensional instability of the material. A second thermal expansion measurement showed slight instability (0.001-inch specimen growth) between 700° and 800°C.

The thermal expansion of lubricant compact No's. 35 and 149 which had 10 and 15% nickel binders respectively are shown in Figure 39. The 10% binder compact material exhibited dimensional instability similar to, but less than, the MoS_2 without binder. A very slight dimensional instability was noted with the 15% binder material at temperatures to 700°C. The expansion of this compact is within 0.002 inches per inch of the titanium carbide K162B material at 700°C.

In order to overcome the dimensional instability observed in the composites they were heat-treated at 1800°F in an argon atmosphere for four hours.

The linear thermal expansion for ten compositions after stabilization and for the titanium carbide cermet K162B bearing material are plotted in Figure 40. The thermal expansion of compositions 144, 204 and 214 were measured at 200°C, 400°C, 600°C and 800°C. No dimensional instability of these materials was evident. In order to expedite the thermal expansion measurements on the remaining compositions, measurements were obtained only at temperatures of 200°C, 400°C and 600°C. This data was then extrapolated to 800°C.

Selection of Composite Materials for Bearing Tests

For the initial Phase II bearing tests the lubricant composite materials were selected on the basis of their fracture strength. Compositions which exhibited fracture strengths in excess of ATJ graphite were selected for Phase II bearing tests 1 through 7.

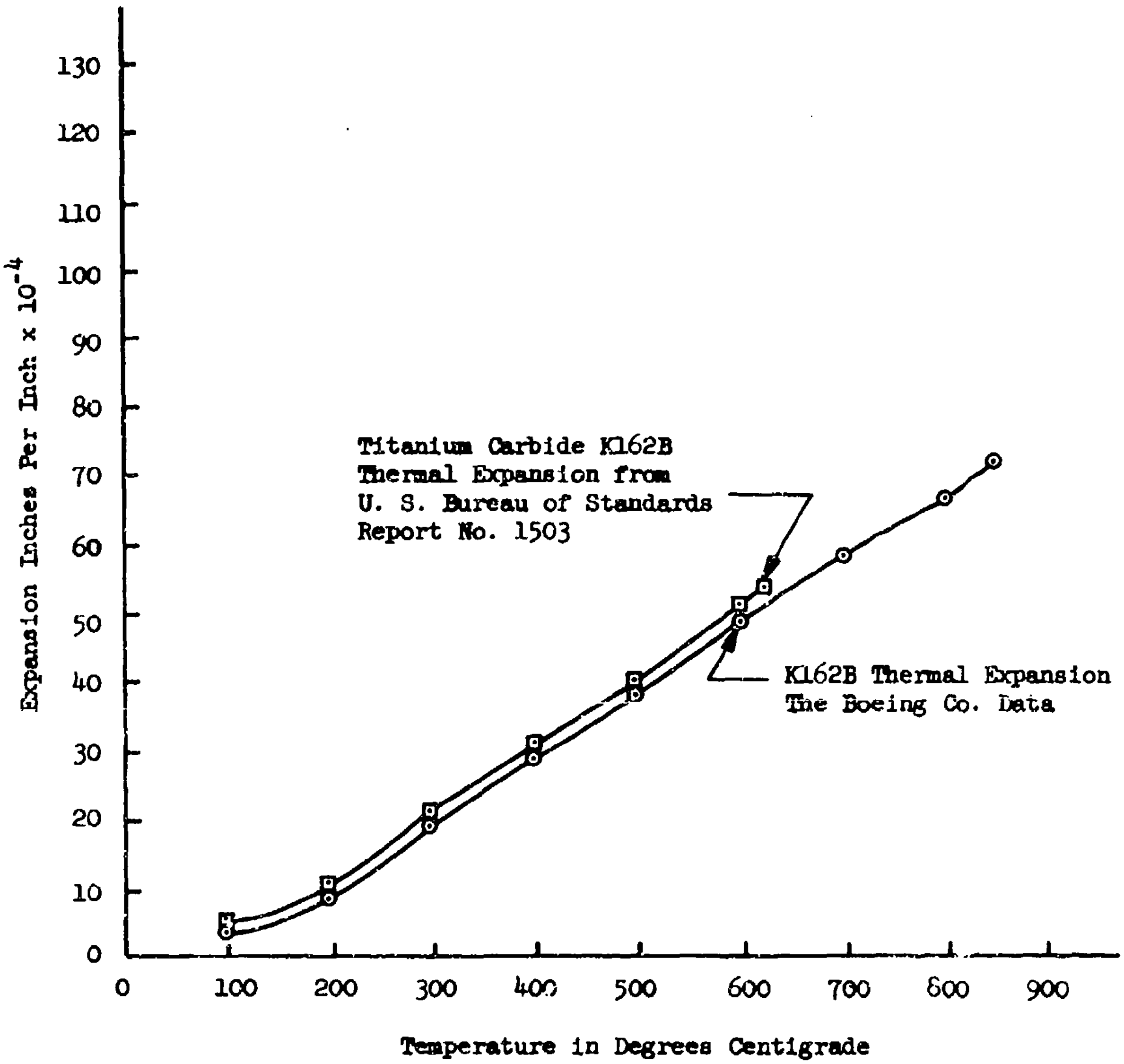


FIGURE 37 THERMAL EXPANSION OF TITANIUM CARBIDE K162B

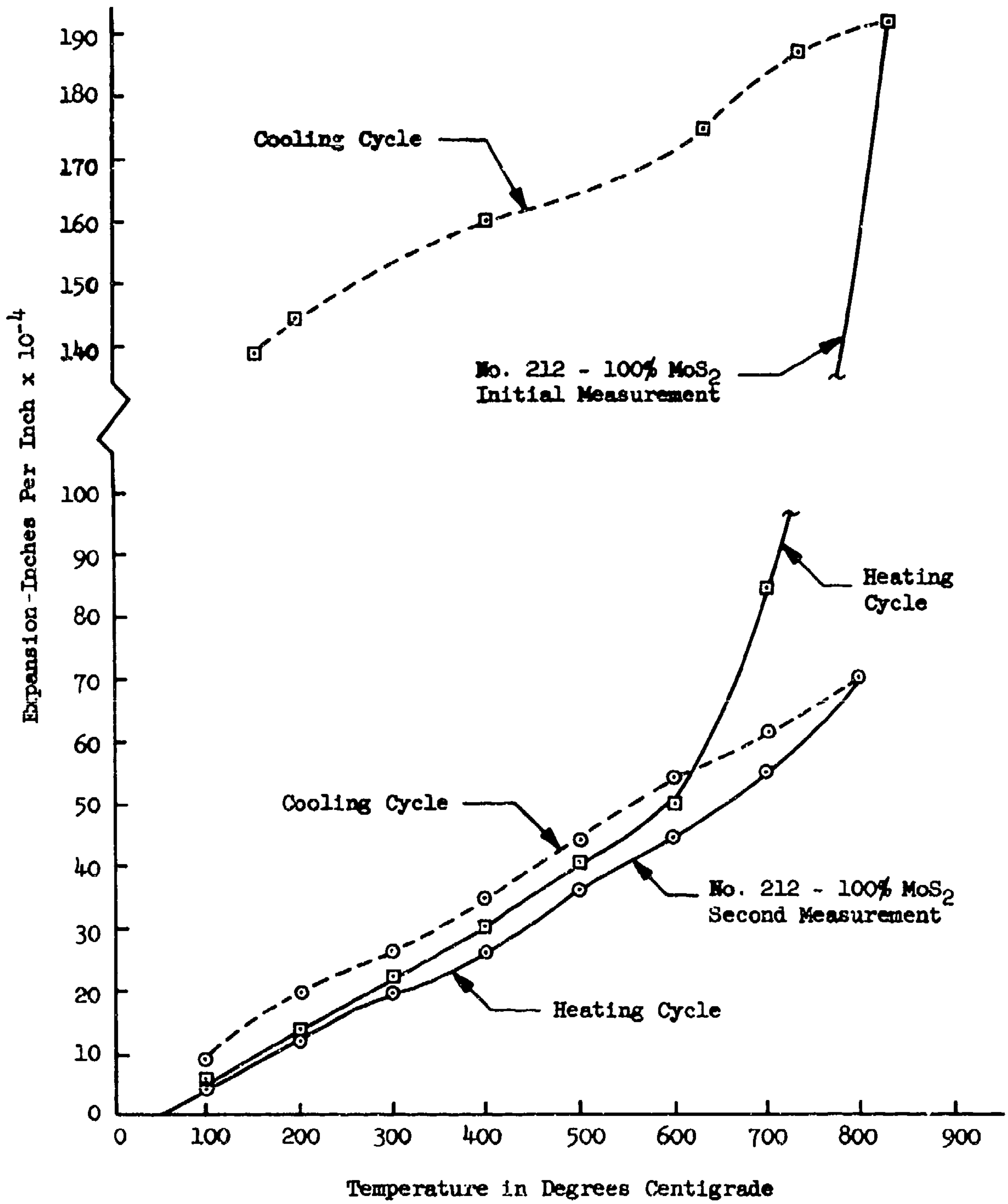


FIGURE 38
THERMAL EXPANSION OF MOLYBDENUM DISULFIDE - NO BINDER

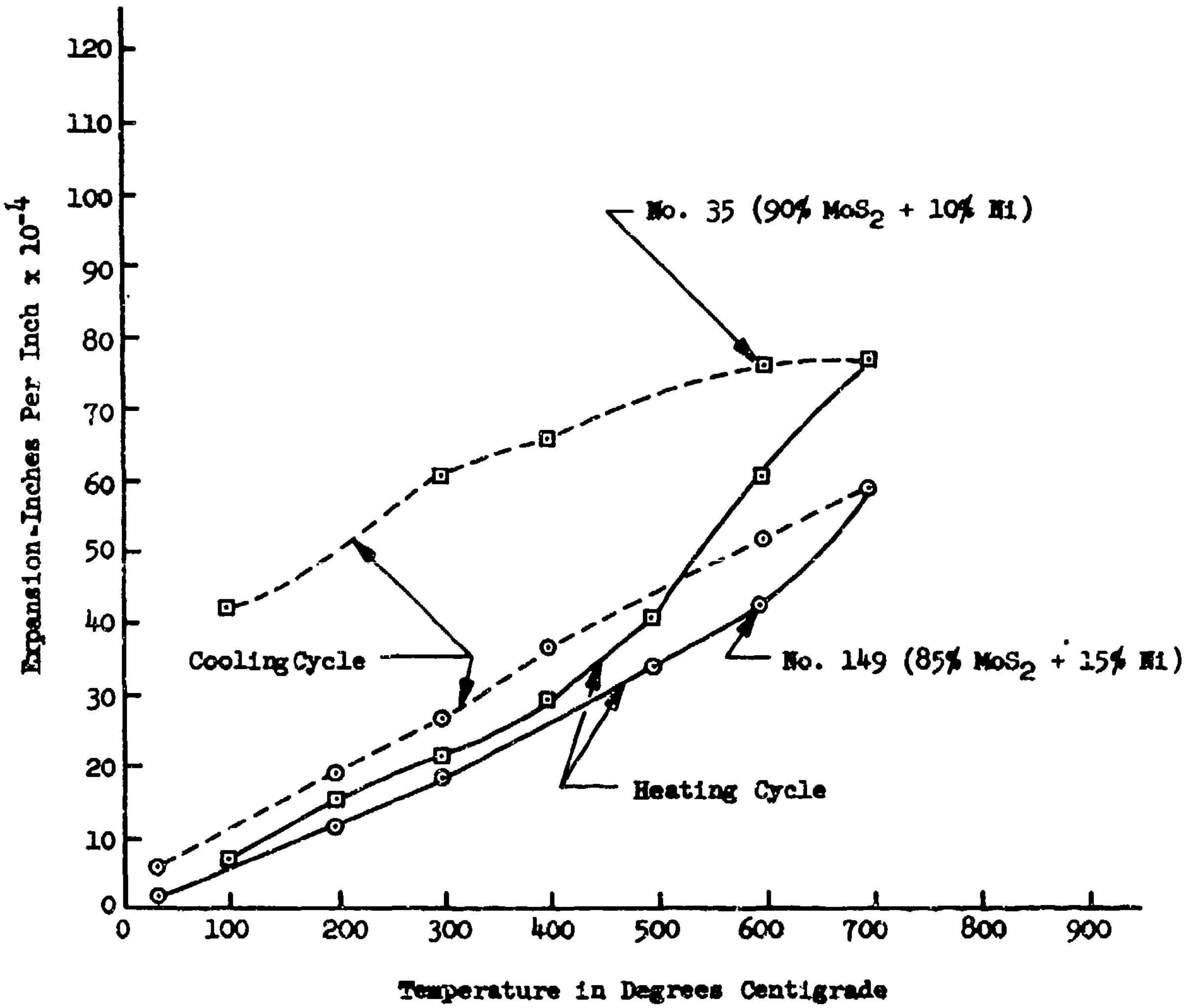


FIGURE 39

THERMAL EXPANSION OF MoS_2 + Ni COMPACTS

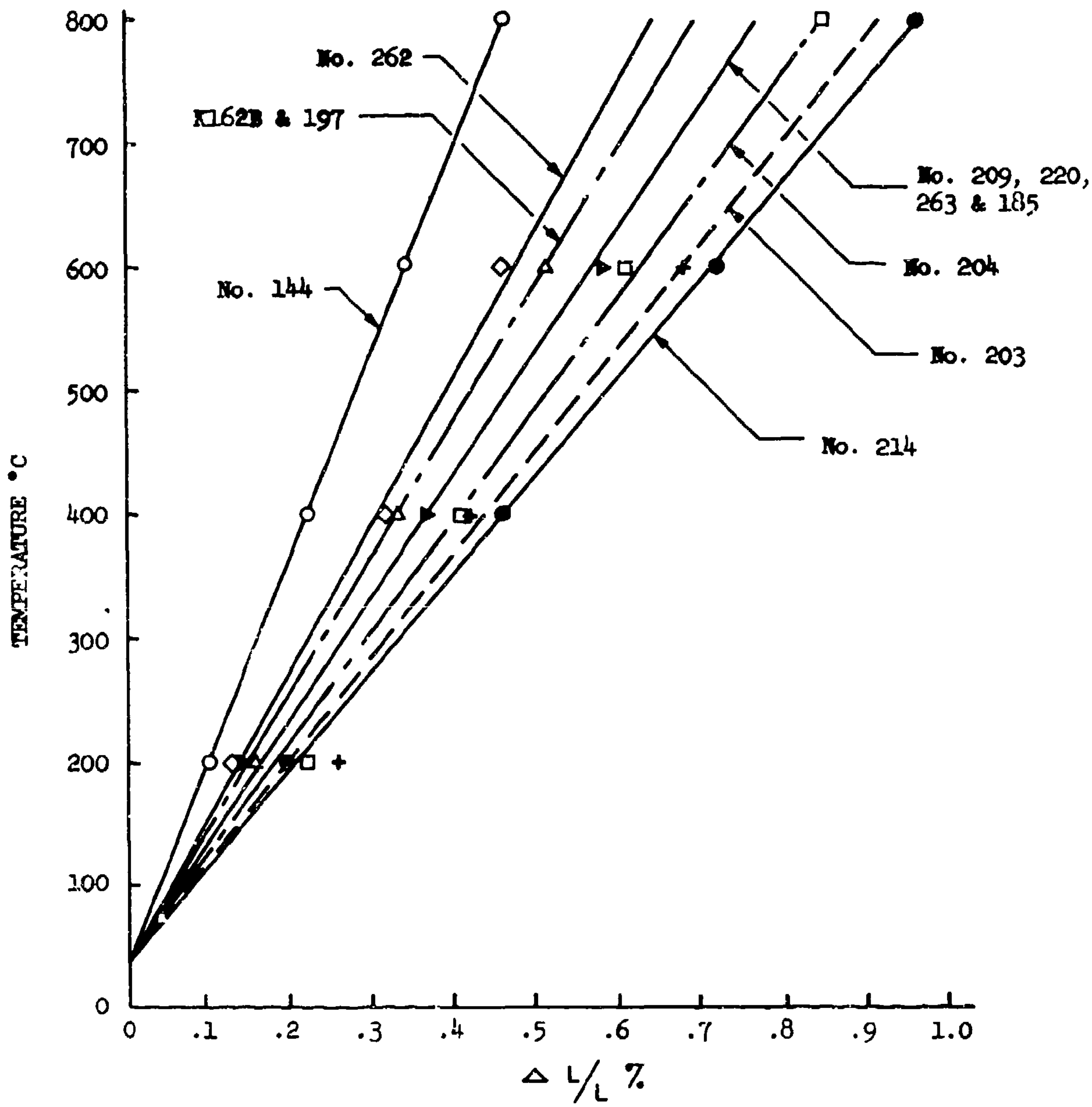


FIGURE 40 LINEAR THERMAL EXPANSION OF LUBRICANT COMPACTS AND TITANIUM CARBIDE CERMET K162B

For Phase II tests 8 through 13 the selection of compositions was based upon the friction and wear tests conducted at Washington State University, as well as, fracture strength data. Friction and wear properties were considered to be the best criteria for the selection of lubricant composites. Because of time required in obtaining this data, an alternate criteria for the selection of lubricant composites was investigated. It appeared reasonable to assume that the performance of a lubricant composite would be related to the percentage of lubricant in the composite and its fracture load. An emperical equation was written to represent the performance rating (PR) ... a lubricant composite:

PR = (percent lubricant) x (fracture load)

This equation was used to compare composites with equal fracture loads. Using this equation the composite material with the highest percentage of lubricant would receive the highest performance rating. Approximately 100 composite materials were rated using the above equation. Only limited correlation was established between the performance rating obtained by the equation and the actual friction and wear measurements made on the material. Redirection of the contract prohibited a complete analysis of this rating technique.

For the Phase II redirected program the lubricant-compact materials were selected on the basis of minimum wear and friction characteristics obtained in previous screening tests conducted at Washington State University at 1500°F and in The Boeing Company laboratories at room temperature.

Separator Material Fabrication

Final hot pressing work on the contract involved the fabrication of lubricant composite specimens 1.75" in diameter by 5/8" thick to be used as the lubricant separators for full scale bearing tests under the redirected program. The following lubricant composites were selected for this portion of the program: No's. 99, 144, 169, 417, 421, 425 and 513. Of these, only specimen No's. 99, 144 and 425 were successfully incorporated and tested in the full scale bearing tests. The remaining composites No's. 169, 417, 421 and 513 all contained numerous cracks when hot-pressed into the larger specimens described above. Insufficient time prohibited further investigation of this problem.

b. Washington State University

Washington State University completely redesigned their high-speed sliding friction machine for operation to 1500°F. This machine used cylindrical test specimens fabricated at Boeing from lubricant composite materials. The composite was held stationary and was loaded against a titanium carbide K162B ring rotating at a surface speed of

7200 feet per minute. With this modification, the sliding friction machine was used to determine the coefficient of friction and wear rates of lubricant composite materials. The extremely small frictional force expected when the lubricant composites were subjected to loads of one pound or less necessitated a precise measurement of minute friction forces. Therefore, in the redesign of the sliding friction machine, considerable attention was given to the friction measuring system. The grinder shown in Figure 41 was added to the machine to facilitate refinishing the K162B rings without their being removed from the test machine. This established better control of test-ring concentricity. Details of the W.S.U. test machine are shown in Figures 42, 43 & 44. These figures show the arrangement of torque bar, motor, drive system, furnace, test specimens, oil lubricator and tool post grinder.

The carbide test ring was mounted on a stainless steel shaft. The mounting method used is the tapered mount described in ASD TR 61-153. This method permitted mounting of rings or bearings on shafts which have different thermal expansion coefficients. The mounting method performed satisfactorily in all of the tests conducted at W.S.U.

Initial runs on the W.S.U. machine were conducted to determine the optimum load necessary to produce .003 inches of wear on ATJ graphite during a forty-minute run. With a load of one pound the wear was found to be 0.094 inches at the end of forty minutes. Table XIX and Figure 45 contain information on run time vs. wear scar width at a one-pound load. Excessive vibration made it impossible to conduct tests at lower loads.

A test firing of the furnace shown in Figure 43 was conducted to determine the time necessary to heat the complete unit including test ring and lubricant composite to 1500°F. The heating cycle used is shown on Figure 46. A total of forty-one runs were made on the W.S.U. tester, these included an initial run on ATJ graphite at room temperature and friction and wear tests at high temperature on lubricant composites. Data covering lubricant composite friction and wear tests can be found in Tables XVIII, XIX and Figure 47.

3. DISCUSSION OF RESULTS

Data covering both dry and hot-pressing of lubricant composites are given in Tables XV, XVI and XVII. The chemical composite, fracture load, and the pressing load temperature-temperature relationship for each composite are included on the aforementioned tables. Theoretical density versus pressing load, and fracture strength versus pressing load for molybdenum disulfide composites are included in Figures 48 and 49 respectively. The distribution of Ni in MoS_2 in mixtures of 10% Ni-90% MoS_2 and 5% Ni in 95% MoS_2 are shown in Figure 50. These photomicrographs illustrate the uniform distribution of the nickel binder (light areas) in the MoS_2 matrix.

Two hundred seventy-two hot-pressed lubricant composites with fracture strengths equal to or greater than the 460 pound fracture strength of ATJ graphite were obtained.

Lead oxide was the only material other than MoS_2 that was successfully compressed into a composite without the use of binders.

Lubricant composites were not adversely affected when heated to 1500°F for one hour in a vacuum of 25 microns.

Forty-one tests were conducted on the W.S.U. high speed, high temperature test machine. The test temperature, wear scar, friction coefficient, surface speed and test duration are shown in Tables XVIII and XIX. Of the above tests two lubricant composites No's. 99 and 144 compared very favorably with ATJ graphite at 1500°F in regards to wear and friction coefficient. Initial testing on the W.S.U. high speed-high temperature machine was hampered by serious vibration problems. Therefore data from the original tests may be inconclusive.

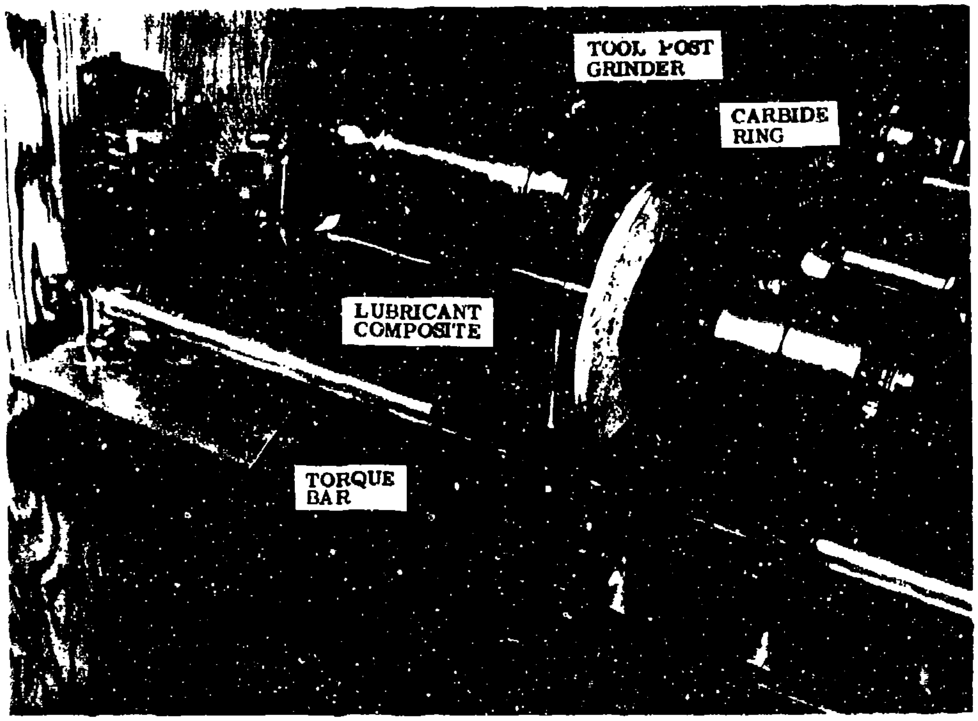


FIGURE 41 W.S.U. HIGH-SPEED HIGH-TEMPERATURE TEST RIG-TORQUE BAR AND GRINDER

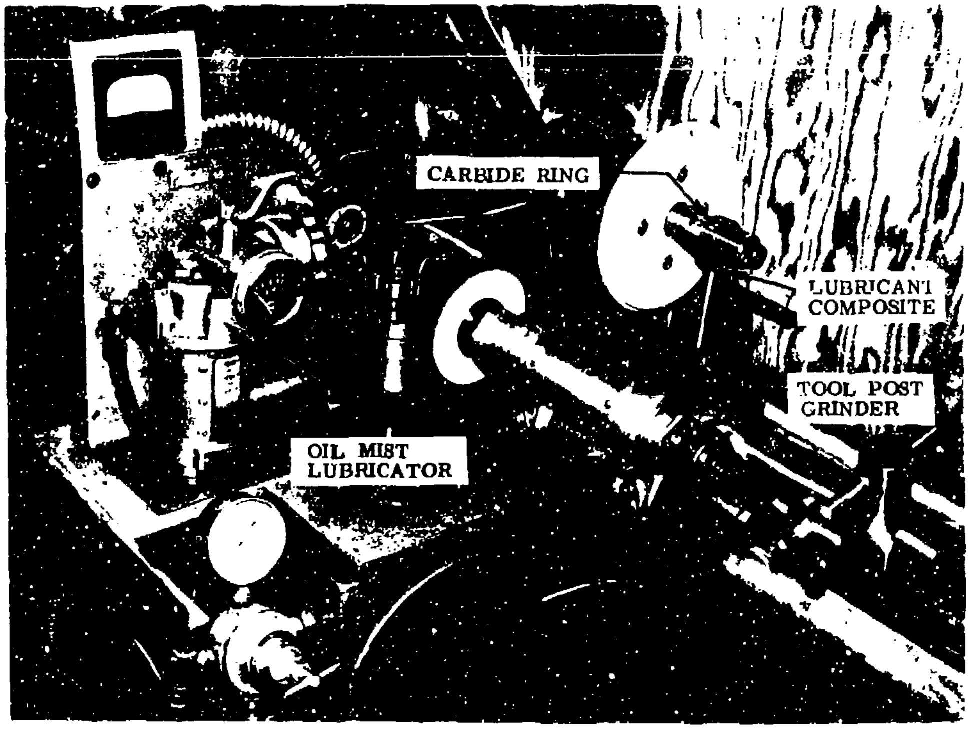


FIGURE 42 W.S.U. HIGH-SPEED HIGH-TEMPERATURE TEST RIG-SPECIMENS AND OIL LUBRICATOR

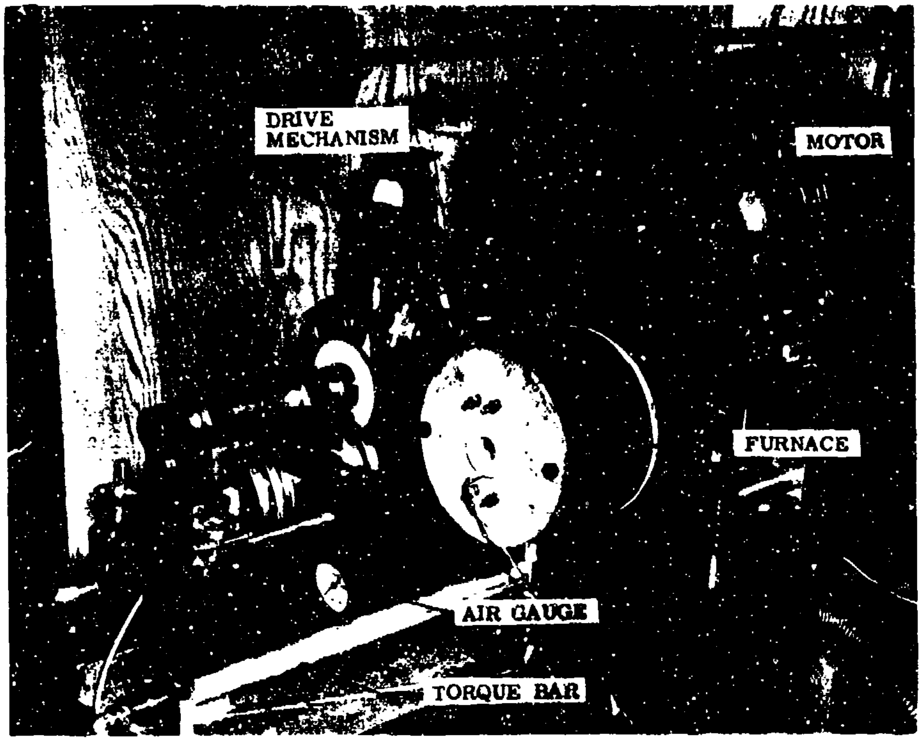


FIGURE 43 W.S.U. HIGH-SPEED HIGH-TEMPERATURE TEST RIG-DRIVE SYSTEM AND FURNACE

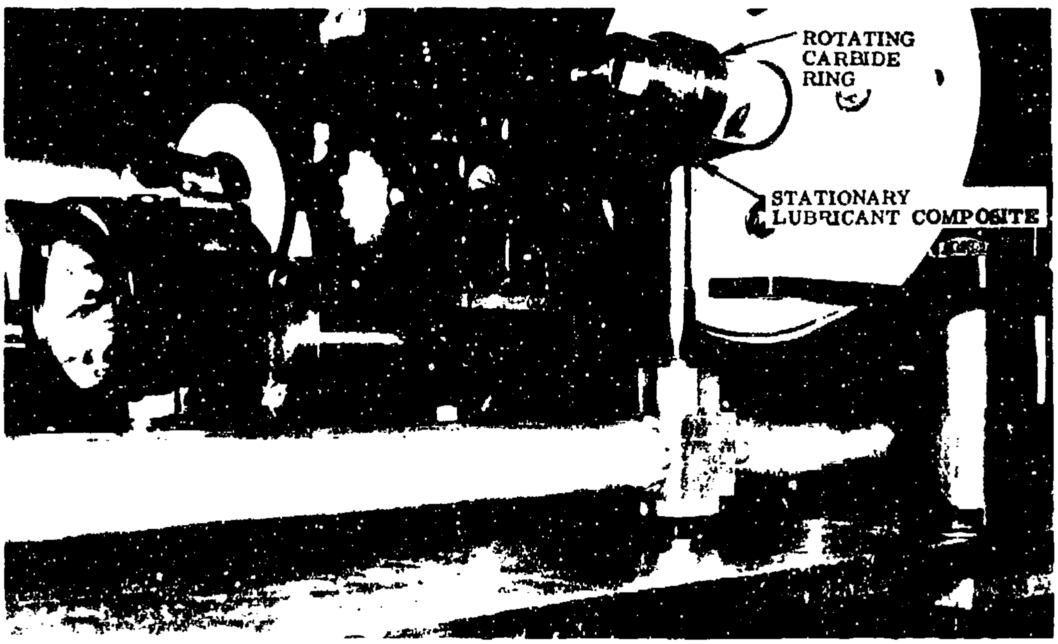


FIGURE 44 W.S.U. HIGH-SPEED HIGH-TEMPERATURE TEST RIG-TEST SPECIMEN CLOSE-UP

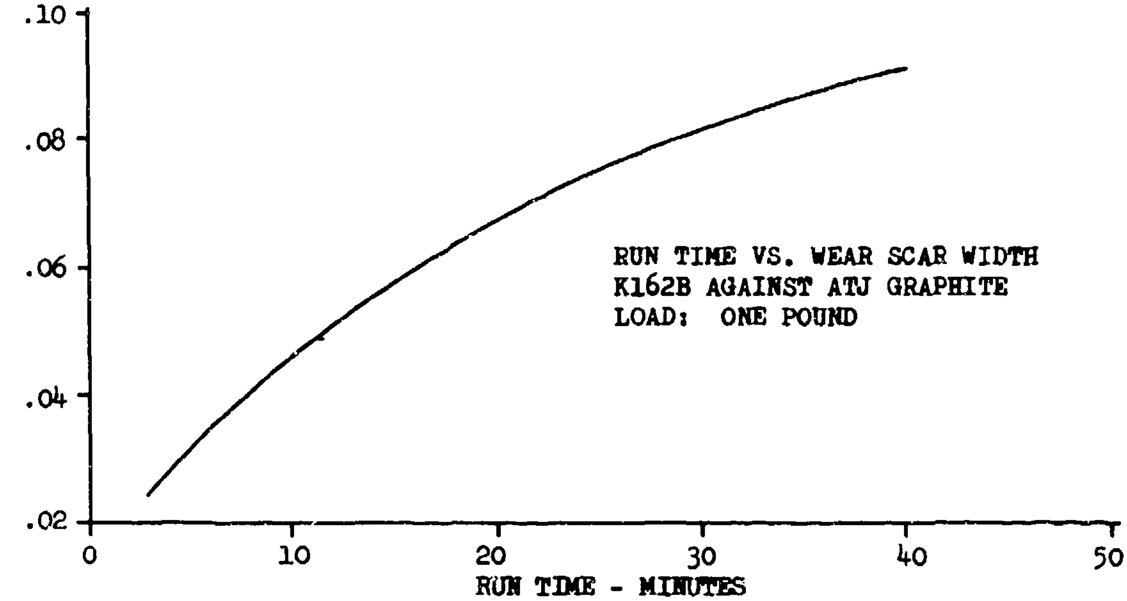


FIGURE 45
WEAR VS. TIME FOR ATJ GRAPHITE

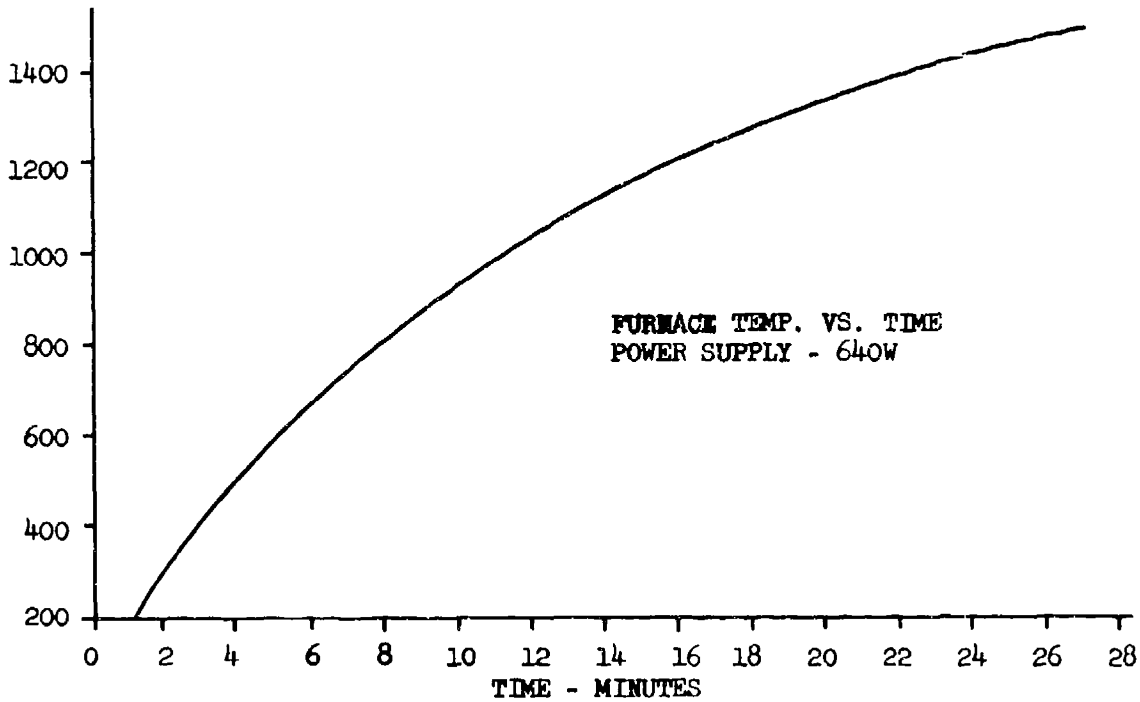


FIGURE 46
FURNACE TEMPERATURE VS. TIME

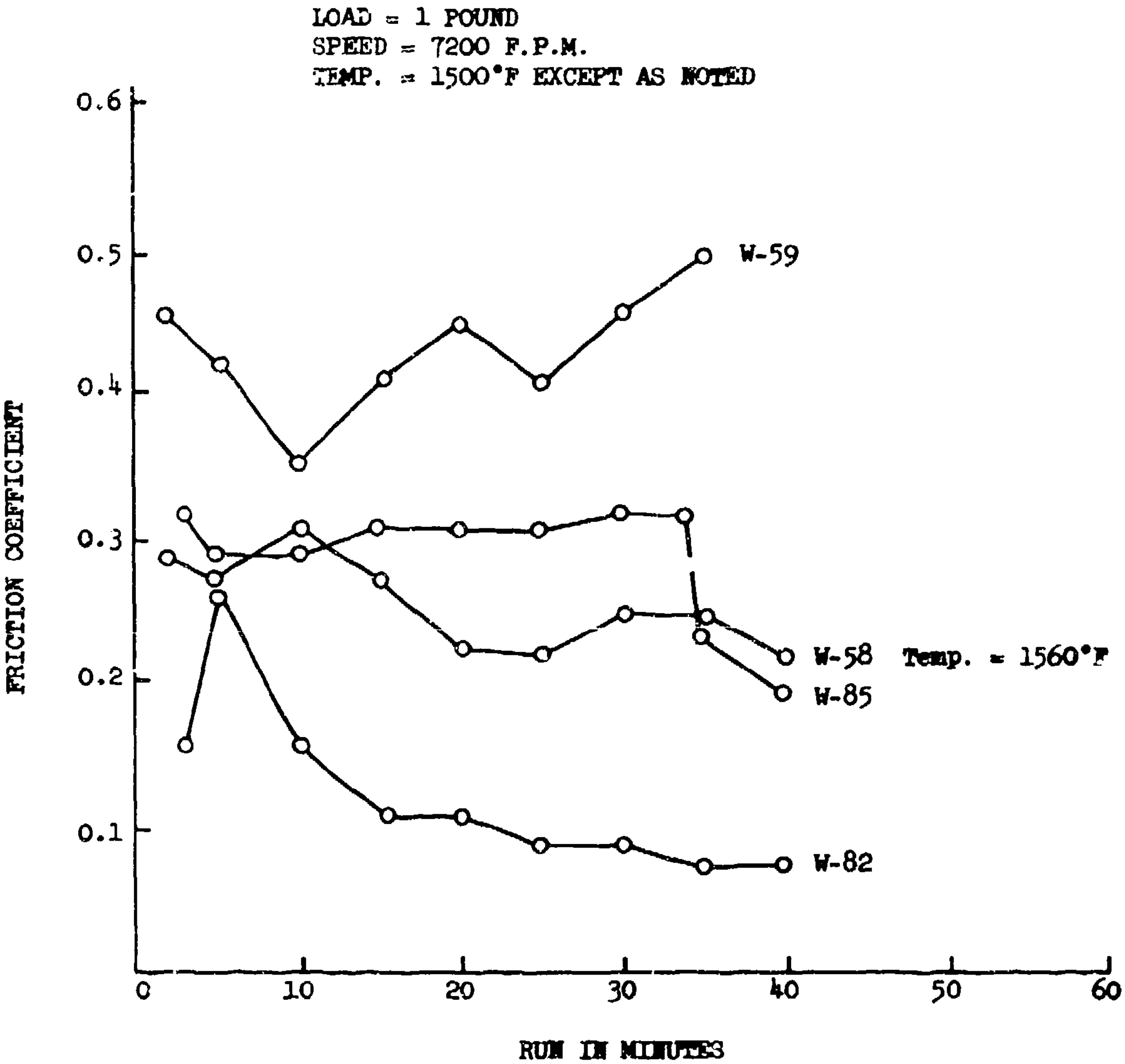


FIGURE 47 FRICTION OF LUBRICANT COMPOSITES

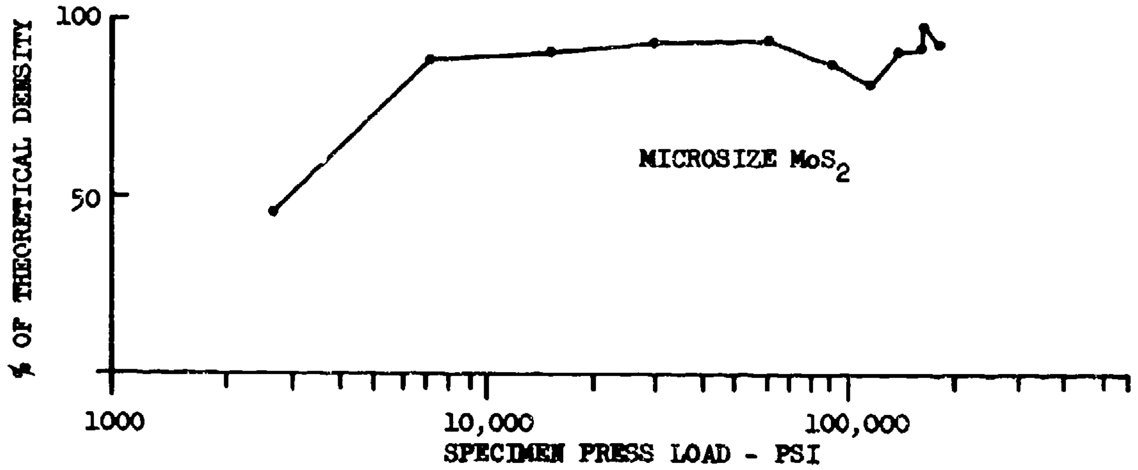


FIGURE 48
PERCENT THEORETICAL DENSITY - VS. PRESS LOAD

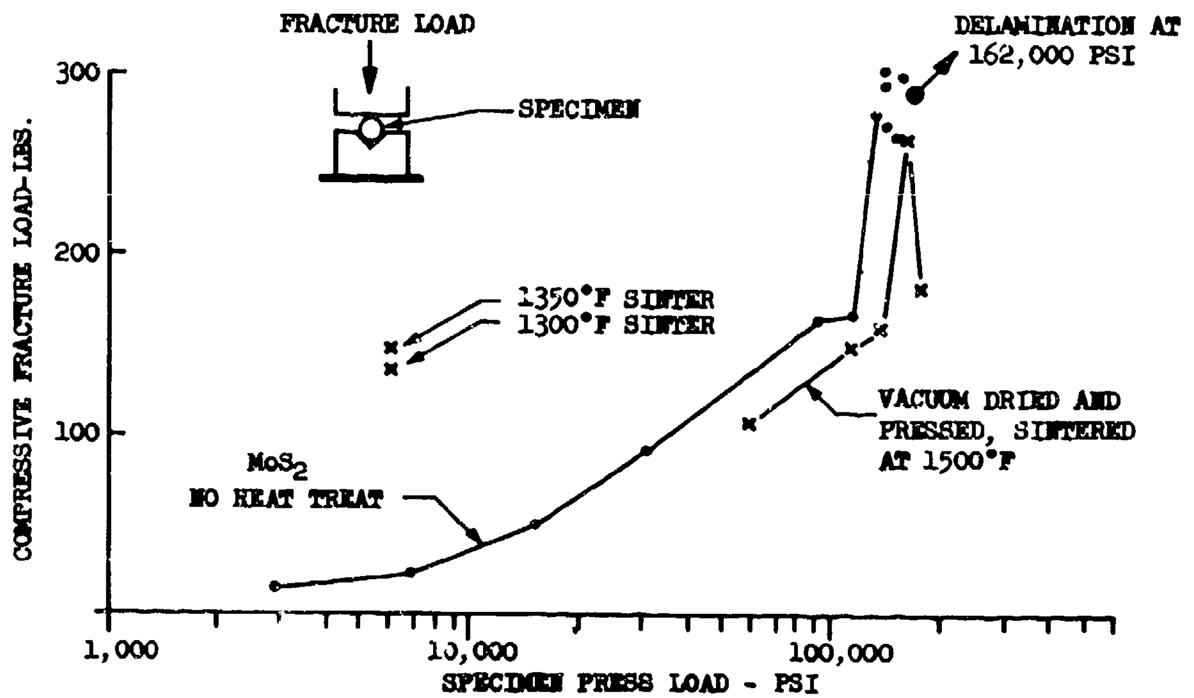
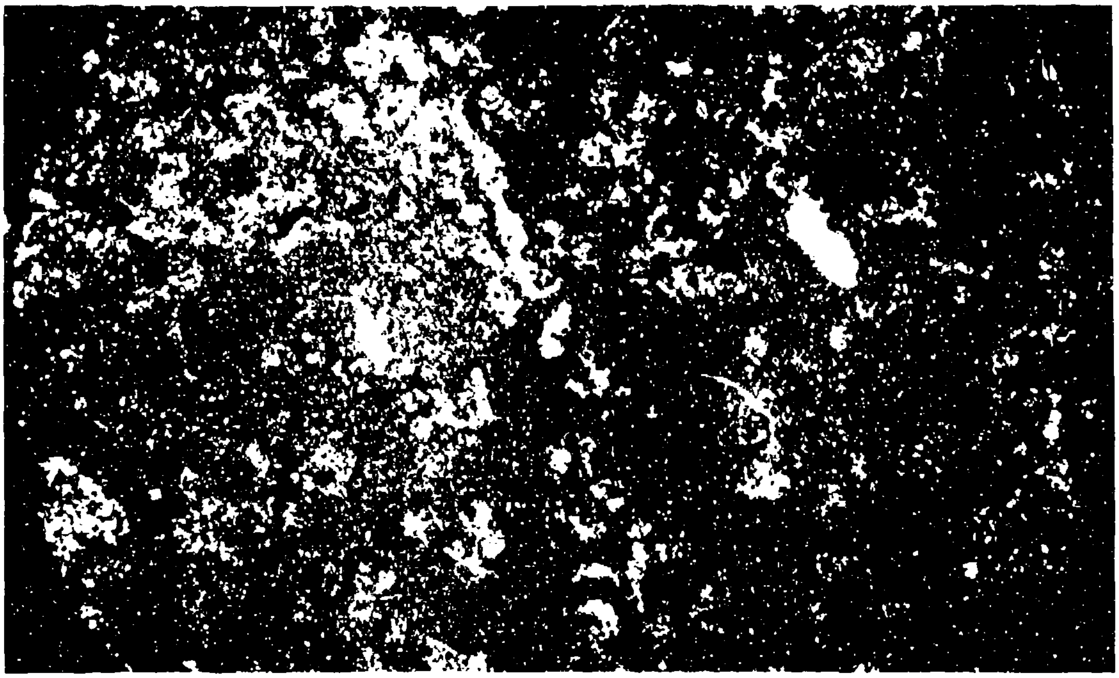
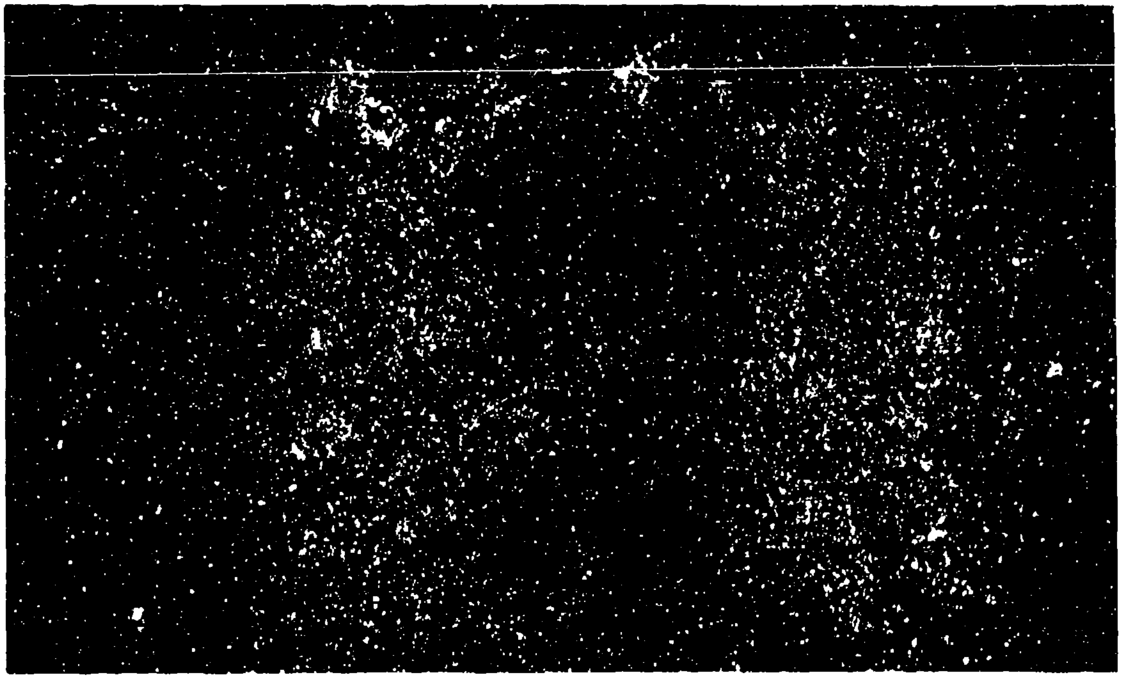


FIGURE 49
COMPRESSIVE STRENGTH VS. PRESS LOAD FOR
MICROSIZE MoS_2



10% Ni-90% MoS_2 50X MAGNIFICATION



5% Ni-95% MoS_2 50X MAGNIFICATION

FIGURE 50 50X MAGNIFICATION OF LUBRICANT COMPOSITES

TABLE XV

DRY PRESS DATA

Test No.	Material	Pressing Load (psi)	Fracture Load (lbs)	Remarks
1	PbS	139,000	211	Pressure delaminated
2	PbO	139,000	255	Hard slug, no pressure delaminations
3	CaF_2	139,000	68	Slug very soft
4	CdO	139,000	169	Pressure delaminated
5	SnO	139,000	11.5	Slug very soft
6	$AgSO_4$	131,000	145	$AgSO_4$ pressure delaminated at all pressing loads.
7	$AgSO_4$	70,000	130	
8	$AgSO_4$	31,000	52.5	
9	Cr_2O_3	139,000	21	Cr_2O_3 did not form a usable slug
10	Cr_2O_3	232,000	0	
11	MoS_2 plus C-9 Binder *	139,000	205	Slug sintered at 900°F to cure binder

TABLE XV CONT.

Test No	Material	Pressing Load (psi)	Fracture Load (lbs)	Remarks
12	MoS_2 plus SiO_2 binder	139,000	83	Slug sintered at 1500°F
13	MoS_2 plus Sodium Silicate **	139,000	152	Slug sintered at 1500°F
14	MoS_2 Plus	139,000	40.5	Slug sintered at 1500°F. Slug broken on removal from die

*C-9 Graphite Binder

**Sodium silicate solution K

TABLE XVI

HOT PRESS DATA

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE (°F)	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
1	MoS_2	7200	1650°F	*	Samples 1 thru 16 were all defective due to improper dies. Pressing Sequence: Preload of 300 lbs. Increased to 530 lbs. at 1650°F.
2	MoS_2	7200	1615°F	*	Pressing Sequence: Preload of 150 lbs. Increased to 365 lbs. at 1550°F.
3 & 4	90% MoS_2 + 10% Ni	7200	1580°F	330	Pressing Sequence: Preload of 173 lbs. Increased to 225 lbs. at 1500°F.
5 & 6	90% MoS_2 + 5% Ni + 5% Au	7200	1615°F	568	Pressing Sequence: Preload of 175 lbs. Increased to 460 lbs. at 1500°F.
7	80% MoS_2 + 10% Ni + 10% PbS	7650	1600°F	336	Pressing Sequence: Preload of 175 lbs. Increased to 420 lbs. at 1550°F.
8	80% MoS_2 + 10% Ni + 10% Au	7650	1600°F	324	Pressing Sequence: Preload of 175 lbs. Increased to 420 lbs. at 1575°F.
9	80% MoS_2 + 10% Ni + 10% Au	7200	1610°F	668	Pressing Sequence: Preload of 175 lbs. Increased to 210 lbs. at 1580°F.
10 & 11	Navy Drilube NAMCAML-23A	7200	1610°F	852	Die fractured. Pressing Sequence: discontinued after test no. 9.
12	89% MoS_2 + 1% SiO_2 + 10% Ni	7200	1600°F	368	
13	89% MoS_2 + 1% Si + 10% Ni	7200	1620°F	142	
14	80% MoS_2 + 10% AgS + 10% Graphite	7200	1610°F	74	
15	96% MoS_2 + 4% Synar	7200	1600°F	*	
16	80% MoS_2 + 10% Ni + 10% Graphite	8000	1600°F	532	
17	Navy Drilube NAMCAML-23A	7200	1710°F	969	Die fractured from slight explosion.
18 & 19	80% MoS_2 + 10% PbS + 10% Ni	7200	1600°F	584	Materials for tests 18 thru 129 vacuum dried prior to pressing.
20 & 29	96% MoS_2 + 4% Synar	7500	1625°F	*	
21 & 36	80% MoS_2 + 10% AgS + 10% Graphite	7200	1625°F	136	
22 & 39	89% MoS_2 + 10% SiO_2 + 10% Ni	7230	1615°F	660	
23 & 33	89% MoS_2 + 1% Si + 10% Ni	7200	1600°F	282.5	
24 & 25	95% MoS_2 + 5% Ni	7200	1620°F	266	
26 & 32	85% MoS_2 + 5% PbO + 10% Ni	7200	1620°F	786	
27 & 31	85% MoS_2 + 10% Ni + 5% $Pb_2(PO_4)_3$	7200	1610°F	924	

*Insufficient material for fracture specimen.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE (°F)	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
28 & 30	80% MoS_2 + 10% Ni + 10% Graphite	7200	1520°F	410	
34	80% MoS_2 + 10% Ni + 10% Au	7200	1520°F	728	
35 & 37	90% MoS_2 + 10% Ni	7200	1600°F	740	
38	80% MoS_2 + 10% Ni + 10% PbS	7200	1520°F		Specimen broke due to worn graphite die.
40	90% MoS_2 + 10% Fe	7200	1520°F	264	
41	96% MoS_2 + 4% SiO_2	7200	1520°F	*	Specimen broke due to worn graphite die.
42	90% MoS_2 + 10% 420 Stainless Steel	7200	1640°F		
43	90% MoS_2 + 10% (50% Ti–50% Ni Alloy)	7200	1620°F	210	
44	90% MoS_2 + 10% (80% Cr–20% Ni Alloy)	7200	1620°F		
45	90% MoS_2 + 10% Fe	7200	1600°F		
46 & 53	90% MoS_2 + 10% (20% Cr + 90% Ni)	7200	1600°F	566	
47	80% MoS_2 + 10% Ni + 10% Au	7200	1600°F		
48 & 52	90% MoS_2 + 10% (50% Zr + 50% Ni)	7200	1600°F	200	
49	90% MoS_2 + 10% (50% Ti + 50% Ni)	7200	1600°F		
50	90% MoS_2 + 10% 420 S. S.	7200	1600°F		Specimen fractured on removal from die.
51 & 55	90% MoS_2 + 10% (80% Cr + 20% Ni)	7200	1600°F		Die fractured.
54	90% MoS_2 + 10% Si	7200	1600°F	106	
56	90% MoS_2 + 10% Mo	7200	1600°F	152	Specimen broken when removed from die.
57	90% MoS_2 + 10% Cr	7200	1600°F		
58	90% MoS_2 + 10% Cr	7200	1600°F	170	
59	Navy Drilube NAMCAML	Die fractured at 150 lb. load.			
60	Navy Drilube NAMCAML	Die fractured at 850 lb. load	1620°F		Die fractured, slight explosion.
61	90% MoS_2 + 10% Lt-1	7200	1600°F	155	
62	90% MoS_2 + 10% Mo	7200	1940°F	186	
63	90% MoS_2 + 10% MoS	7200	1600°F	104	
64	90% MoS_2 + 10% XP 1106	7200	1600°F	82	Specimen broke when removed from die.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE (°F)	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
65	90% MoS_2 + 10% Nb	7200	1600°F	88	Specimen broken when removed from die.
66	90% MoS_2 + 10% 18-8 S.S.	7200	1600°F	96	Same as above.
67	90% MoS_2 + 10% ZrB	7200	1600°F	94	Same as above.
68	90% MoS_2 + 10% TiB_2	7600	1600°?	182	
69	10% MoS_2 + 10% (20% Cr + 80% Ni)	7200	1600°F		
70	90% MoS_2 + 10% CrB	7200	1600°F	174	
71 & 129	90% MoS_2 + 2% Si + 8% Ni	7200	1600°F	720	
72	90% MoS_2 + 2.7% Si + 7.3% Mo	7200	1600°F	172	
73	90% MoS_2 + 10% (55% Cr + 45% Si)	7200	1600°F	188	
74	90% MoS_2 + 10% K-162B	7200	1600°F	227	
75	80% MoS_2 + 10% Ni + 10% $Pb_2(PO_4)_3$	7200	1600°F	424	
76	90% MoS_2 + 10% 201	7200	1600°F	100	
77	90% MoS_2 + 10% 16C	7200	1600°F	364	
78	85% MoS_2 + 10% Mo + 5% $Pb_2(PO_3)_4$	7200	2000°F	444	
79	90% MoS_2 + 10% 11 - 18	7200	2000°F	290	
80 & 113	85% MoS_2 + 10% Si + 5% $Pb_2 PO_3)_4$	7200	2000°F	926	
81	90% MoS_2 + 10% XP111C	7200	2000°F	234	
82	90% MoS_2 + 10% 15C	7200	2000°F	720	
83 & 116	90% MoS_2 + 10% Metco 43C	7200	2000°F	720	
84	90% MoS_2 + 1.% Pr	7200	2000°F	200	
85	90% MoS_2 + 10% Pd	7200	2000°F	353	
86	90% MoS_2 + 10% $MoSi_2$	7200	2000°F	260	
87 & 112	90% MoS_2 + 10% (60% Fe + 40% Cr)	7200	2000°F	1260	
88 & 127	90% MoS_2 + 10% (80% Si + 20% Al)	7200	2000°F	420	
89 & 121	90% MoS_2 + 10% (55% Al + 45% Fe)	7200	2000°F	430	
90 & 120	90% MoS_2 + 10% (55% Cr + 45% Al)	7200	2000°F	580	
91 & 114	90% MoS_2 + 10% (87% Ni + 13% Al)	7200	2000°F	580	
92	90% MoS_2 + 10% (42% Ni + 58% Al)	7200	2000°F	[illegible]	
94	90% MoS_2 + 10% (80% Fe + 20% Al)	7200	2000°F	380	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
95 & 122 & 129	90% MoS_2 + 10% (70% Pd + 30% Al)	7200	2000°F	420	
96 & 110	90% MoS_2 + 10% (80% Fe + 20% Pd)	7200	2000°F	1160	
97 & 111	90% MoS_2 + 10% (50% Pd + 50% Cr)	7200	2000°F	1050	
98 & 125	90% MoS_2 + 10% (30% Pt + 70% Au)	7200	2000°F	540	
99 & 109	90% MoS_2 + 10% (80% Fe + 20% Pt)	7200	2000°F	1520	
100	90% MoS_2 + 10% (60% Pt + 40% Cr)	7200	2000°F	370	
101	90% MoS_2 + 10% (60% Pt + 40% Cu)	7200	2000°F	440	
102 & 123	90% MoS_2 + 10% (35% Mo + 65% Fe)	7200	2000°F	980	
103 & 126	90% MoS_2 + 10% (60% Ni + 40% Cu)	7200	2000°F	720	
104	90% MoS_2 + 10% (50% W + 50% Al)	7200	2000°F	280	
105 & 124	85% MoS_2 + 10% Ni + 5% $Cd_3(PO_4)_2$	7200	2000°F	750	
106 & 118	85% MoS_2 + 10% Mo + 5% $Cd_3(PO_4)_2$	7200	2000°F	450	
107 & 117	85% MoS_2 + 10% Si + 5% $Cd_3(PO_4)_2$	7200	2000°F	960	
108 & 119	No. 1005	7200	2000°F	920	
115 & 93	90% MoS_2 + 10% (42% Ni + 58% Al)	7200	2000°F	800	
132	50% MoS_2 + 50% (80% Fe + 20% Pt)	7200	2000°F	3760	
133 & 148	75% MoS_2 + 25% (80% Fe + 20% Pt)	7200	2000°F	390	
134	80% MoS_2 + 20% (80% Fe + 20%Pt)	7200	2000°F	1300	
135 & 149	85% MoS_2 + 15% (80% Fe + 20% Pt)	7200	2000°F	635*	
136 & 146	75% MoS_2 + 25% (60% Fe + 40% Cu)	7200	2000°F	1340*	
137	80% MoS_2 + 10% Ni + 10% $PbMoO_4$	7200	2000°F	680	
138 & 147	80% MoS_2 + 20% (60% Fe + 40% Cu)	7200	2000°F	1490*	
139	85% MoS_2 + 15% (80% Fe + 20% Pd)	7200	2000°F	1500	

*Average of 2 separate specimens.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
140	88% MoS_2 + 10% Ni + 2% $Pb_2(PO_4)_3$	7200	2000°F	1175	
141	85% MoS_2 + 15% Ni	7200	2000°F	850	
142	80% MoS_2 + 20% Ni	7230	2000°F	1130	
143	73% MoS_2 + 27% Ni	7200	2000°F	1100	
144	80% MoS_2 + 20% (80% Fe + 20% Pd)	7200	2000°F	3430	
145	75% MoS_2 + 25% (80% Fe + 20% Pd)	7200	2000°F	2200	
150	80% MoS_2 + 10% Ni + 10% Pb MoO_4	7200	2000°F	680	
151	80% MoS_2 + 20% Ni	7200	2000°F	1280	
152	80% MoS_2 + 20% (20% Pd + 80% Fe)	7200	2000°F	1660	
153	85% MoS_2 + 15% (80% Fe + 20% Pd)	7200	2000°F	1360	
154	85% MoS_2 + 15% Ni	7200	2000°F	900	
155	73% MoS_2 + 27% Ni	7200	2000°F	780	
156	75% MoS_2 + 25% (80% Fe + 20% Pd)	7200	2000°F	2560	
157	80% MoS_2 + 20% (60% Fe + 20% Pt)	7200	2000°F	1100	
158	88% MoS_2 + 10% Ni + 2% Pb_2 $(PO_4)_3$	7200	2000°F	1280	
159	50% MoS_2 + 50% (80% Fe + 20% Pt)	7200	2000°F	3900	
160	85% MoS_2 + 15% (60% Fe + 40% Cu)	7200	2000°F	940	
161	70% MoS_2 + 30% (65% Fe + 35% Mo)	7200	2000°F		Die fractured breaking lubricant specimen
162	80% MoS_2 + 20% (65% Fe + 35% Mo)	7200	2000°F	2780	
163	75% MoS_2 + 25% (65% Fe + 35% Mo)	7200	2000°F	1350	
164	75% MoS_2 + 25% (60% Fe + 40% Cu)	7200	2000°F	1160	
165	10% MoS_2 + 90% Ni	7200	2000°F	10,150	Specimen did not fracture (malleable)
166	20% MoS_2 + 80% Ni	7200	2000°F	6000	Specimen did not fracture (malleable)
167	30% MoS_2 + 70% Ni	7200	1700°F	6000	Specimen did not fracture (malleable)
168	25% MoS_2 + 75% (60% Ni + 40% Cu)	7200	1700°F	870	
169	70% MoS_2 + 30% (65% Fe + 35% Mo)	7200	1300°F	2300	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
170	10% MoS_2 + 90% (60% Fe + 40% Cu)	7200	1800	6000	
171 & 181	5% MoS_2 + 95% TIC*	7200	2000	750	
172 & 182	10% MoS_2 + 90% TIC*	7200	2000	850	
173	20% MoS_2 + 80% TIC*	7200	2000	2000	
174	30% MoS_2 + 70% TIC*	7200	2000	5200	
175	40% MoS_2 + 60% TIC*	7200	2000	3000	
176	50% MoS_2 + 50% TIC*	7200	2000	2800	
177	60% MoS_2 + 40% TIC*	7200	2000	1100	
178	70% MoS_2 + 30% TIC*	7200	2000	350	
179	80% MoS_2 + 20% TIC*	7200	2000	400	
180	20% MoS_2 + 80% (60% Fe + 40% Cu)	7200	2000	8000 +	Note 1.
183	20% TiO_2 + 80% Ni	7200	1800	5000	Specimen did not fracture (Malleable)
184	40% TiO_2 + 60% Ni	7200	1800	3860	
185	60% TiO_2 + 40% Ni	7200	1800	3860	
186	80% TiO_2 + 20% Ni	7200	1800	2000	
187	20% NiO + 80% Ni	7200	1800	5000	Specimen did not fracture (Malleable)
188	60% NiO + 40% Ni	7200	1800	160	
189	40% MoS_2 + 40% TiO_2 + 20% Ni	7200	1800	1800	
190	30% MoS_2 + 30% TiO_2 + 40% Ni	7200	1800	1600	
191	20% MoS_2 + 20% TiO_2 + 60% Ni	7200	1800	4650	
192	10% MoS_2 + 10% TiO_2 + 80% Ni	7200	1800	3860	
193	80% Ni + 15% TiO_2 + 5% NiO	7200	1900	8000 +	Note 1.
194	40% MoS_2 + 60% (60% Ni + 40% Cu)	7200	1900	3500	
195	60% MoS_2 + 40% (60% Ni + 40% Cu)	7200	1850	2500	
196	20% MoS_2 + 80% (60% Ni + 40% Cu)	7200	1850	8000 +	Note 1.

*Composition of TIC - 25% Ni, 5% Mo, 64% TiC, 6% NbC.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
197	40% MoS_2 + 60% (80% Fe + 20% Pd)	7200	2000°F	8340	
198	20% MoS_2 + 80% (80% Fe + 20% Pd)	7200	2000°F	7800	
199	20% MoS_2 + 80% (67% Ni + 33% Cd_3 $(PO_4)_3$	7200	1850°F	2550	
200	40% MoS_2 + 60% (67% Ni + 33% Cd_3 $(PO_4)_3$	7200	2000	900	
201	60% MoS_2 + 40% (67% Ni + 33% Cd_3 $(PO_4)_2$	7200	1850	800	
202	80% MoS_2 + 20% (67% Ni + 33% Cd_3 $(PO_4)_2$	7200	2000	500	
203	60% MoS_2 + 40% (80% Fe + 20% Pt)	7200	2000	8800	Note 1.
204	40% MoS_2 + 60% (80% Fe + 20% Pt)	7200	2000	8000 +	Note 1.
205	20% MoS_2 + 80% (80% Fe + 20% Pt)	7200	2000	8000 +	Note 1.
206	20% MoS_2 + 80% (65% Fe + 35% Mo)	7200	2000	7500	
207	40% MoS_2 + 60% (65% Fe + 35% Mo)	7200	2000	3000	
208	60% MoS_2 + 40% (65% Fe + 35% Mo)	7200	2000	300	
209	No. 5 White Solid Lubricant with Ceramic Binder.	7200	2000	2240	
210	60% MoS_2 + 40% (50% Pt + 50% Pd	7200	2000	200	
211	80% MoS_2 + 20% (50% Pt + 50% Pd)	7200	2000	320	
212	100% MoS_2 Micro size	7200	2000	360	Specimen fabricated for the specific purpose of determining thermal expansion of MoS_2
213	20% MoS_2 + 80% (60% Fe + 40% Cu)	7200	2000	8000 +	Note 1.
214	40% MoS_2 + 60% (60% Fe + 40% Cu)	7200	2000	8000 +	Note 1.
215	20% MoS_2 + 80% (67% Si + 33% Cd_3 $(PO_4)_3$	7200	1900	2550	
216	40% MoS_2 + 60% (67% Si + 33% Cd_3 $(PO_4)_2$	7200	1900	----	Specimen Exploded Fracturing the die.
217	60% MoS_2 + 40% (67% Si + 33% Cd_3 $(PO_4)_2$	7200	2000	61	
218	80% MoS_2 + 20% (67% Si + 33% Cd_3 $(PO_4)_2$	7200	2000	735	
219	20% MoS_2 + 80% 43C	7200	2000	2780	
220	40% MoS_2 + 60% 43C	7200	2000	5700	
221	60% MoS_2 + 40% 43C	7200	2000	3600	
222	60% MoS_2 + 20% 43C	7200	2000	1550	
223	20% MoS_2 + 80% (80% Ni + 20% Cr)	7200	2000	9400	Specimen did not fracture (Malleable)

NOTE 1. Fracture tests were terminated at 8000 lbs load after it was found that deformation of the "V" block had occurred.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (LBS)	REMARKS
224	40% MoS_2 + 60% (80% Ni + 20% Cr)	7200	2000°F	6480	
225	60% MoS_2 + 40% (80% Ni + 20 % Cr)	7200	2000°F	2650	
226	80% MoS_2 + 20% (80% Ni + 20% Cr)	7200	2000°F	1260	
227	20% MoS_2 + 80% (80% Ni + 20% Si)	7200	2000°F	2870	
228	40% MoS_2 + 60% (80% Ni + 20% Si)	7200	2000°F	560	
229	60% MoS_2 + 40% (80% Ni + 20% Si)	7200	2000°F	380	
230	80% MoS_2 + 20% (80% Ni + 20% Si)	7200	2000°F	350	
231	20% MoS_2 + 80% (42% Ni + 58% Al)	7200	2000°F	370	Improper mixing procedure resulted in very weak specimen.
232	40% MoS_2 + 60% (42% Ni + 58% Al)	7200	2000°F	3500	
233	-----	----	------	----	Specimen to be fabricated.
234	60% MoS_2 + 40% (42% Ni + 58% Al)	7200	2000°F	300	Evidence of a chemical reaction between components.
235	80% MoS_2 + 20% (42% Ni + 58% Al)	7200	2000°F	500	
236	20% MoS_2 + 40% Ni + 40% Au	7200	2000°F	1750	
237	40% MoS_2 + 30% Ni + 30% Au	7200	2000°F	1350	
238	60% MoS_2 + 20% Ni + 20% Au	7200	2000°F	820	
239	80% MoS_2 + 10% Ni + 10% Au	7200	2000°F	600	
240	20% MoS_2 + 80% (67% Si + 33% $Pb_3(PO_4)_2$)	7200	2000°F	----	Specimen exploded, fracturing the die.
241	40% MoS_2 + 60% (67% Si + 33% $Pb_3(PO_4)_2$)	7200	2000°F	----	Specimen exploded, fracturing the die.
242	60% MoS_2 + 40% (67% Si + 33% $Pb_3(PO_4)_2$)	7200	1800°F	370	
243	80% MoS_2 + 20% (67% Si + 33% $Pb_3(PO_4)_2$)	7200	1800°F	780	
244	20% MoS_2 + 80% (67% Ni + 33 % PbO)	7200	2000°F	1100	
245	40% MoS_2 + 60% (67% Ni + 33% PbO)	7200	2000°F	640	
246	60% MoS_2 + 40% (67% Ni + 33% PbO)	7200	2000°F	780	
247	80% MoS_2 + 20% (67% Ni + 33% PbO)	7200	2000°F	700	
248	20% MoS_2 + 72% Ni + 8% SiO_2	7200	1800°F	5950	Specimen was malleable.
249	40% MoS_2 + 54% Ni + 6% SiO_2	7200	1800°F	2380	
250	60% MoS_2 + 36% Ni + 4% SiO_2	7200	1800°F	970	
251	80% MoS_2 + 18% Ni + 2% SiO_2	7200	1800°F	550	
252	40% NiO + 60% Ni	7200	1800°F	1580	
253	80% NiO + 20% Ni	7200	1800°F	2220	
254	40% NiO + 20% Ni + 40% TiO_2	7200	1800°F	----	Specimen exploded, fracturing the die.
255	30% NiO + 30% TiO_2 + 40% Ni	7200	1800°F	820	
256	20% NiO + 20% TiO_2 + 60% Ni	7200	1800°F	4020	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
257	10% NiO + 10% TiO_2 + 80% Ni	7200	1800°F	1800	Specimen maleable
258	60% NiO + 20% TiO_2 + 20% Ni	7200	1800°F	[illegible]	
259	15% TiO_2 + 45% NiO + 40% Ni	7200	1800°F	350	
260	10% TiO_2 + 30% NiO + 60% Ni	7200	1800°F	3720	
261	5% TiO_2 + 15% NiO + 80% Ni	7200	1800°F	740	Specimen malleable
262	60% TiO_2 + 20% NiO + 20% Ni	7200	1800°F	2900	
263	45% TiO_2 + 15% NiO + 40% Ni	7200	1800°F	1070	
264	30% TiO_2 + 10% NiO + 60% Ni	7200	1800°F	4700	
265	15% TiO_2 + 5% NiO + 80% Ni	7200	1800°F	5100	
266	20% TiO_2 + 60% MoS_2 + 20% Ni	7200	1800°F	1310	
267	15% TiO_2 + 45% MoS_2 + 40% Ni	7200	1800°F	480	
268	10% TiO_2 + 30% MoS_2 + 60% Ni	7200	1800°F	5270	
269	5% TiO_2 + 15% MoS_2 + 80% Ni	7200	1800°F	7900	Specimen malleable
270	60% TiO_2 + 20% MoS_2 + 20% Ni	7200	1800°F	2850	
271	45% TiO_2 + 15% MoS_2 + 40% Ni	7200	1800°F	1200	
272	30% TiO_2 + 10% MoS_2 + 60% Ni	7200	1800°F	4300	
273	15% TiO_2 + 5% MoS_2 + 80% Ni	7200	1800°F	1400	
274	27% TiO_2 + 27% MoS_2 + 27% NiO + 19% Ni	7200	1800°F	350	
275	20% TiO_2 + 20% MoS_2 + 20% NiO + 40% Ni	7200	1800°F	50	
276	13% TiO_2 + 13% MoS_2 + 13% NiO + 61% Ni	7200	1800°F	7760	
277	7% TiO_2 + 7% MoS_2 + 7% NiO + 79% Ni	7200	1800°F	2900	
278	16% TiO_2 + 32% NiO + 32% MoS_2 + 20% Ni	7200	1800°F	740	
279	12% TiO_2 + 24% NiO + 24% MoS_2 + 40% Ni	7200	1800°F	140	
280	8% TiO_2 + 16% NiO + 16% MoS_2 + 60% Ni	7200	1800°F	4260	
281	4% TiO_2 + 8% NiO + 8% MoS_2 + 80% Ni	7200	1800°F	10,000	Specimen malleable
282	32% TiO_2 + 24% NiO + 24% MoS_2 + 20% Ni	7200	1800°F	1460	
283	24% TiO_2 + 18% NiO + 18% MoS_2 + 40% Ni	7200	1800°F	1260	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
284	16% TiO_2 + 12% NiO + 12% MoS_2 + 60% Ni	7200	1800°F	1400	
285	8% TiO_2 + 6% NiO + 6% MoS_2 + 80% Ni	7200	1800°F	9700	Specimen malleable
286	48% TiO_2 + 16% NiO + 16% MoS_2 + 20% Ni	7200	1800°F	720	
287	36% TiO_2 + 12% NiO + 12% MoS_2 + 40% Ni	7200	1800°F	40	Specimen crumbled
288	24% TiO_2 + 8% NiO + 8% MoS_2 + 60% Ni	7200	1800°F	440	
289	12% TiO_2 + 4% NiO + 4% MoS_2 + 80% Ni	7200	1800°F	7600	Specimen malleable
290	64% TiO_2 + 8% NiO + 8% MoS_2 + 20% Ni	7200	1800°F	2180	
291	48% TiO_2 + 6% NiO + 6% MoS_2 + 40% Ni	7200	1800°F	3720	
292	32% TiO_2 + 4% NiO + 4% MoS_2 + 60% Ni	7200	1800°F	6390	
293	16% TiO_2 + 2% NiO + 2% MoS_2 + 80% Ni	7200	1800°F	7520	Specimen malleable
294	32% TiO_2 + 16% NiO + 32% MoS_2 + 20% Ni	7200	1800°F	1040	
295	24% TiO_2 + 12% NiO + 24% MoS_2 + 40% Ni	7200	1800°F	290	
296	16% TiO_2 + 8% NiO + 16% MoS_2 + 60% Ni	7200	1800°F	290	
297	8% TiO_2 + 4% NiO + 8% MoS_2 + 80% Ni	7200	1800°F	5870	
298	50% Au + 50% WC	----	----	9000	Specimen malleable
299	TiB_2-Graphite	----	----	420	
300	$MoSi_2$-Graphite	----	----	420	
301	24% TiO_2 + 32% NiO + 24% MoS_2 + 20% Ni	7200	1800°F	1650	
302	18% TiO_2 + 24% NiO + 18% MoS_2 + 40% Ni	7200	1800°F	1400	
303	12% TiO_2 + 16% NiO + 12% MoS_2 + 60% Ni	7200	1800°F	4700	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD IN (lbs)	REMARKS
304	6% TiO_2 + 8% NiO + 6% MoS_2 + 80% Ni	7200	1800°F	8800	Specimen malleable
305	16% TiO_2 + 48% NiO + 16% MoS_2 + 20% Ni	7200	1800°F	500	
306	12% TiO_2 + 36% NiO + 12% MoS_2 + 40% Ni	7200	1800°F	1780	
307	8% TiO_2 + 24% NiO + 8% MoS_2 + 60% Ni	7200	1800°F	3850	
308	4% TiO_2 + 12% NiO + 4% MoS_2 + 80% Ni	7200	1800°F	1100	Specimen very malleable
309	8% TiO_2 + 64% NiO + 8% MoS_2 + 20% Ni	7200	1800°F	1500	
310	6% TiO_2 + 48% NiO + 6% MoS_2 + 40% Ni	7200	1800°F	600	
311	4% TiO_2 + 32% NiO + 4% MoS_2 + 60% Ni	7200	1800°F	4700	
312	2% TiO_2 + 16% NiO + 2% MoS_2 + 80% Ni	7200	1800°F	1750	Specimen malleable
313	8% TiO_2 + 8% NiO + 64% MoS_2 + 20% Ni	7200	1800°F	1050	
314	6% TiO_2 + 6% NiO + 48% MoS_2 + 40% Ni	7200	1800°F	300	
315	4% TiO_2 + 4% NiO + 32% MoS_2 + 60% Ni	7200	1800°F	5130	
316	2% TiO_2 + 2% NiO + 16% MoS_2 + 80% Ni	7200	1800°F	11,000	Specimen malleable
317	16% TiO_2 + 16% NiO + 48% MoS_2 + 20% Ni	7200	1800°F	1000	
318	12% TiO_2 + 12% NiO + 36% MoS_2 + 40% Ni	7200	1800°F	800	
319	8% TiO_2 + 8% NiO + 24% MoS_2 + 60% Ni	7200	1800°F	9200	
320	4% TiO_2 + 4% NiO + 12% MoS_2 + 80% Ni	7200	1800°F	6200	Specimen malleable
321	24% TiO_2 + 24% NiO + 32% MoS_2 + 20% Ni	7200	1800°F	870	
322	18% TiO_2 + 18% NiO + 24% MoS_2 + 40% Ni	7200	1800°F	130	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (LBS)	REMARKS
323	12% TiO_2 + 12% NiO + 16% MoS_2 + 60% Ni	7200	1800°F	5670	
324	6% TiO_2 + 6% NiO + 8% MoS_2 + 80% Ni	7200	1800°F	7300	Specimen malleable
325	32% TiO_2 + 32% NiO + 16% MoS_2 + 20% Ni	7200	1800°F	3750	
326	24% TiO_2 + 24% NiO + 12% MoS_2 + 40% Ni	7200	1800°F	3200	
327	16% TiO_2 + 16% NiO + 8% MoS_2 + 60% Ni	7200	1800°F	9970	
328	8% TiO_2 + 8% NiO + 4% MoS_2 + 80% Ni	7200	1800°F	11,000	Specimen malleable
329	80% MoS_2 + 20% (53% Nb + 47% Ni)	7200	1300°F	550	
330	60% MoS_2 + 40% (53% Nb + 47% Ni)	7200	1300°F	370	
331	40% MoS_2 + 60% (53% Nb + 47% Ni)	7200	1300°F	5740	
332	20% MoS_2 + 80% (53% Nb + 47% Ni)	7200	1300°F	3470	
333	80% MoS_2 + 20% (90% Si + 10% Ni)	7200	1800°F	1015	
334	60% MoS_2 + 40% (90% Si + 10% Ni)	7200	1800°F	2100	
335	40% MoS_2 + 60% (90% Si + 10% Ni)	7200	1800°F	1045	
336	20% MoS_2 + 80% (90% Si + 10% Ni)	7200	1800°F	870	
337	80% MoS_2 + 20% (47% Mo + 53% Ni)	7200	1860°F	1115	
338	60% MoS_2 + 40% (47% Mo + 35% Ni)	7200	1860°F	1930	
339	40% MoS_2 + 60% (47% Mo + 53% Ni)	7200	1880°F	1895	
340	20% MoS_2 + 80% (47% Mo + 53% Ni)	7200	1880°F	1770	
341	80% MoS_2 + 20% (90% Ni + 10% Ni)	7200	1840°F	845	
342	60% MoS_2 + 40% (90% Ni + 10% Pt)	7200	1840°F	1410	
343	40% MoS_2 + 60% (90% Ni + 10% Pt)	7200	1820°F	5160	
344	20% MoS_2 + 80% (90% Ni + 10% Pt)	7200	1820°F	9200	Specimen malleable
345	80% MoS_2 + 20% (85% Ti + 15% Ni)	7200	2000°F	1045	
346	60% MoS_2 + 40% (85% Ti + 15% Ni)	7200	2000°F	870	
347	40% MoS_2 + 60% (85% Ti + 15% Ni)	7200	2030°F	2245	
348	20% MoS_2 + 80% (85% Ti + 15% Ni)	7200	2030°F	6570	
349	80% MoS_2 + 20% (80% Fe + 20% Nb)	7200	2030°F	1635	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
350	60% MoS_2 + 40% (80% Fe + 20% Nb)	7200	2000°F	1650	
351	40% MoS_2 + 60% (80% Fe + 20% Nb)	7200	2000°F	5700	
352	20% MoS_2 + 80% (80% Fe + 20% Nb)	7200	2000°F	5850	
353 - 378	Duplicates of previously fabricated specimens numbers 144, 185, 193, 203, 204, 209, 214, 220, 262 and 263. Additional slugs of the above were fabricated for bearing tests.				
379	20% MoS_2 + 80% (65% Ni + 35% Ta)	7200	2000°F	425	
380	40% MoS_2 + 60% (65% Ni + 35% Ta)	7200	2000°F	805	
381	60% MoS_2 + 40% (65% Ni + 35% Ta)	7200	2000°F	3850	
382	80% MoS_2 + 20% (65% Ni + 35% Ta)	7200	2000°F	4535	
383	80% MoS_2 + 20% (80% Ti + 20% Cu)	7200	2000°F	520	
384	60% MoS_2 + 40% (80% Ti + 20% Cu)	7200	2000°F	625	
385	40% MoS_2 + 60% (80% Ti + 20% Cu)	7200	1800°F	1025	
386	20% MoS_2 + 80% (80% Ti + 20% Cu)	7200	1800°F	1775	
387	80% MoS_2 + 20% (75% Fe + 25% Ta)	7200	1950°F	400	
388	60% MoS_2 + 40% (75% Fe + 25% Ta)	7200	1950°F	1490	
389	40% MoS_2 + 60% (75% Fe + 25% Ta)	7200	1950°F	10,000	Test stopped; specimen did not fracture.
390	20% MoS_2 + 80% (75% Fe + 25% Ta)	7200	1950°F	3,000	
391	100% MoS_2	2000	2500°F	250	
392	100% MoS_2	2000	2[illegible]00°F	315	
393	80% MoS_2 + 20% ALON "C"	2000	2600°F	180	
394	60% MoS_2 + 40% ALON "C"	2000	2600°F	300	
395	40% MoS_2 + 60% ALON "C"	2000	2500°F	21[illegible]	
396	20% MoS_2 + 80% ALON "C"	2000	2500°F	230	
397	80% MoS_2 + 20% TiB_2	2000	2500°F	610	
398	60% MoS_2 + 40% TiB_2	2000	2500°F	630	
399	40% MoS_2 + 60% TiB_2	2000	2500°F	580	
400	20% MoS_2 + 80% TiB_2	2000	2[illegible]00°F	210	
401	80% MoS_2 + 20% $MoSi_2$	2000	2500°F	160	
402	60% MoS_2 + 40% $MoSi_2$	2000	2500°F	200	
403	40% MoS_2 + 60% $MoSi_2$	2000	2500°F	420	
404	[illegible]0% MoS_2 + 80% $MoSi_2$	2000	2500	410	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
405	80% (80% MoS_2 · 20% B_2O_3) + 20% Ni	3500	1800°F	1700	
406	60% (80% MoS_2 · 20% B_2O_3) + 40% Ni	3500	1800°F	[illegible]	
407	40% (80% MoS_2 · 20% B_2O_3) + 60% Ni	2700	1800°F	7350	
408	20% (80% MoS_2 · 20% B_2O_3) + 80% Ni	2700	1800°F	10,000	Specimen malleable.
409	80% (80% MoS_2 · 20% B_2O_3) + 20% (60% Fe · 40% Cu)	2000	2000°F		Specimen exploded fracturing die.
410	60% (80% MoS_2 · 20% B_2O_3) + 40% (60% Fe · 40% Cu)	2000	2000°F		Specimen exploded fracturing die.
411	40% (80% MoS_2 · 20% B_2O_3) + 60% (60% Fe · 40% Cu)	3500	2000°F	6500	
412	20% (80% MoS_2 · 20% B_2O_3) + 80% (60% Fe · 40% Cu)	3500	2000°F	10,000	
413	80% (80% MoS_2 · 20% B_2O_3) + 20% (80% Fe · 20% Pd)	1350	2000°F		Specimen exploded fracturing die.
414	60% (80% MoS_2 · 20% B_2O_3) + 40% (80% Fe · 20% Pd)	1350	2000°F		Specimen exploded fracturing die.
415	80% TiO_2 + 20% (60% Fe · 40% Cu)	7200	2000°F	5300	
416	60% TiO_2 + 40% (60% Fe · 40% Cu)	7200	2000°F	7350	
417	40% TiO_2 + 60% (60% Fe · 40% Cu)	7200	2000°F	5600	
418	20% TiO_2 + 80% (60% Fe · 40% Cu)	7200	2000°F	7000	
419	80% (50% MoS_2 · 50% TiO_2) + 20% (60% Fe · 40% Cu)	7200	2000°F	2900	
420	60% (50% MoS_2 · 50% TiO_2) + 40% (60% Fe · 40% Cu)	7200	2000°F	4850	
421	40% (50% MoS_2 · 50% TiO_2) + 60% (60% Fe · 40% Cu)	7200	2000°F	8830	
422	20% (50% MoS_2 · 50% TiO_2) + 80% (60% Fe · 40% Cu)	7200	2000°F	7820	
423	80% (25% MoS_2 · 75% TiO_2) + 20% 60% Fe · 40% Cu)	7200	2000°F	3400	
424	60% (25% MoS_2 · 75% TiO_2) + 40% (60% Fe · 40% Cu)	7200	2000°F	5150	
425	40% (25% MoS_2 · 75% TiO_2) + 60% (60% Fe · 40% Cu)	7200	2000°F	10,000	
426	20% (25% MoS_2 · 75% TiO_2) + 80% (60% Fe · 40% Cu)	7200	2000°F	7700	

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD	MAXIMUM PRESSING	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
427	80% (75% MoS_2·25% TiO_2) + 20% (60% Fe·40% Cu)	7200	2000°F	2000	
428	60% (75% MoS_2·25% TiO_2) + 40% (60% Fe·40% Cu)	7200	2000°F	2700	
429	40% (75% MoS_2·25% TiO_2) + 60% (60% Fe·40% Cu)	7200	2000°F	10,000	
430	20% (75% MoS_2·25% TiO_2) + 80% (60% Fe·40% Cu)	7200	2000°F	9400	
431	80% MoS_2 + 20% (90% Ti·5% Pt)	7200	2000°F	450	
432	60% MoS_2 + 40% (95% Ti·5% Pt)	7200	2000°F	2360	
433	40% MoS_2 + 60% (95% Ti·5% Pt)	1600	2400°F	5100	
434	20% MoS_2 + 80% (95% Ti·5% Pt)	1600	2400°F	9250	
435	80% MoS_2 + 20% (95% Ti·5% Pd)	2400	2500°F	1900	
436	60% MoS_2 + 40% (95% Ti·5% Pd)	2400	2500°F	1200	
437	40% MoS_2 + 60% (95% Ti·5% Pd)	2000	2500°F	7700	
438	20% MoS_2 + 80% (95% Ti·5% Pd)	2000	2500°F	700	
439	40% (80% MoS_2·20% B_2O_3) + 60% (80% Fe·20% Pd)	7200	2000°F	10,000	
440	20% (80% MoS_2·20% B_2O_3) + 80% (80% Fe·20% Pd)	7200	2000°F	10,000	
441	K-163B1* + TiC*				Compounded but not hot-pressed.
442	K-163B1* + TiC*				Compounded but not hot-pressed.
443	40% MoS_2 + 60% (80% Fe·20% Pt)				Duplicate of number 204.
444	40% MoS_2 + 60% (60% Fe·40% Cu)				Duplicate of number 214.
445	40% MoS_2 + 60% (80% Fe·20% Pd)				Duplicate of 197.
446	10% MoS_2 + 90% K-163B**	——	2330°F	7900	Specimen brittle.
447	80% (40% TiO_2·40% NiO·20% MoS_2) + 20% (60% Fe·40% Cu)	7200	1800°F	3000	
448	60% (40% TiO_2·40% NiO·20% MoS_2) + 40% (60% Fe·40% Cu)	7200	1800°F	5270	
449	40% (40% TiO·40% NiO·20% MoS_2) + 60% (60% Fe·40% Cu)	7200	2000°F	8200	Specimen malleable.
450	20% (40% TiO_2·40% NiO·20% MoS_2) 80% (60% Fe·40% Cu)	7200	2000°F	9750	

*Compounded by Boeing using the following materials: 33.3% Ni, 6.7% Mo, 54% TiC and 6% NbC.

**Part fabricated by vendor, pressing load not furnished.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (LBS)	REMARKS
451	80% (40% TiO_2·40% NiO·20% MoS_2) + 20% (80% Fe·20% Pd)				Compounded but not hot-pressed.
452	60% (40% TiO_2·40% NiO·20% MoS_2) + 40% (80% Fe·20% Pd)				Compounded but not hot-pressed.
453	40% (40% TiO_2·40% NiO·20% MoS_2) + 60% (80% Fe·20% Pd)				Compounded but not hot-pressed.
454	20% (40% TiO_2·40% NiO·20% MoS_2) + 80% (80% Fe·20% Pd)				Compounded but not hot-pressed.
455	80% (40% TiO_2·40% NiO·20% MoS_2) + 20% (80% Fe·20% Pd)				Compounded but not hot-pressed.
456	60% (40% TiO_2·40% NiO·20% MoS_2) + 40% (80% Fe·20% Pt)				Compounded but not hot-pressed.
457	40% (40% TiO_2·40% NiO·20% MoS_2) 60% (80% Fe·20% Pt)				Compounded but not hot-pressed.
458	20% (40% TiO_2·40% NiO·20% MoS_2) + 80% (80% Fe·20% Pt)				Compounded but not hot-pressed.
459	80% (40% TiO_2·40% NiO·20% MoS_2) + 20% (80% Fe·20% Nb)				Compounded but not hot-pressed.
460	60% (40% TiO_2·40% NiO·20% MoS_2) + 40% (80% Fe·20% Nb)				Compounded but not hot-pressed.
461	40% (40% TiO_2·40% NiO·20% MoS_2) + 60% (80% Fe·20% Nb)				Compounded but not hot-pressed.
462	20% (40% TiO_2·40% NiO·20% MoS_2) + 80% (80% Fe·20% Nb)				Compounded but not hot-pressed.
463	80% (40% TiO_2·40% NiO·20% MoS_2) + 20% (85% Ti·15% Ni)				Compounded but not hot-pressed.
464	60% (40% TiO_2·40% NiO·20% MoS_2) + 40% (85% Ti·15% Ni)				Compounded but not hot-pressed.
465	40% (40% TiO_2·40% NiO·20% MoS_2) + 60% (85% Ti·15% Ni)				Compounded but not hot-pressed.
466	20% (40% TiO_2·40% NiO·20% MoS_2) + 80% (85% Ti·15% Ni)				Compounded but not hot-pressed.
467	80% (80% TiO_2·10% NiO·10% MoS_2) + 20% (60% Fe·40% Cu)				Compounded but not hot-pressed.
468	60% (80% TiO_2·10% NiO·10% MoS_2) + 40% (60% Fe·40% Cu)				Compounded but not hot-pressed.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
469	40% (80% TiO_2·10% NiO·10% MoS_2) + 60% (60% Fe·40% Cu)				Compounded but not hot-pressed.
470	20% (80% TiO_2·10% NiO·10% MoS_2) + 80% (60% Fe·40% Cu)				Compounded but not hot-pressed.
471	80% (80% TiO_2·10% NiO·10% MoS_2) + 20% (80% Fe·20% Pd)				Compounded but not hot-pressed.
472	60% (80% TiO_2·10% NiO·10% MoS_2) + 40% (80% Fe·20% Pd)				Compounded but not hot-pressed.
473	40% (80% TiO_2·10% NiO·10% MoS_2) + 60% (80% Fe·20% Pd)				Compounded but not hot-pressed.
474	20% (80% TiO_2·10% NiO·10% MoS_2) + 80% (80% Fe·20% Pd)				Compounded but not hot-pressed.
475	80% (80% TiO_2·10% NiO·10% MoS_2) + 20% (80% Fe·20% Pt)				Compounded but not hot-pressed.
476	60% (80% TiO_2·10% NiO·10% MoS_2) + 40% (80% Fe·20% Pt)				Compounded but not hot-pressed.
477	40% (80% TiO_2·10% NiO·10% MoS_2) + 60% (80% Fe·20% Pt)				Compounded but not hot-pressed.
478	20% (80% TiO_2·10% NiO·10% MoS_2) + 80% (80% Fe·20% Pt)				Compounded but not hot-pressed.
479	80% (80% TiO_2·10% NiO·10% MoS_2) + 20% (80% Fe·20% Nb)				Compounded but not hot-pressed.
480	60% (80% TiO_2·10% NiO·10% MoS_2) + 40% (80% Fe·20% Nb)				Compounded but not hot-pressed.
481	40% (80% TiO_2·10% NiO·10% MoS_2) + 60% (80% Fe·20% Nb)				Compounded but not hot-pressed.
482	20% (80% TiO_2·10% NiO·10% MoS_2) + 80% (80% Fe·20% Nb)				Compounded but not hot-pressed.
483	80% MoS_2 + 20% K-16381*	2000	2200°F	850	
484	60% MoS_2 + 40% K-16381*	2000	2200°F	1950	
485	40% MoS_2 + 60% K-16381*	2700	2250°F	5360	
486	20% MoS_2 + 80% K-16381*	2700	2250°F	1480	
487	80% (50% MoS_2·50% TiO_2) + 20% (80% Fe·20% Pt)				Compounded but not hot-pressed.
488	60% (50% MoS_2·50% TiO_2) + 20% (80% Fe·20% Pt)				Compounded but not hot-pressed.
489	40% (50% MoS_2·50% TiO_2) + 60% (80% Fe·20% Pt)				Compounded but not hot-pressed.

*Compounded by Boeing

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
490	20% (50% MoS_2·50% TiO_2) + 80% (80% Fe·20% Pt)				Compounded but not hot-pressed.
491	80% (75% TiO_2·25% MoS_2) + 20% (80% Fe·20% Pt)				Compounded but not hot-pressed.
492	60% (75% TiO_2·25% MoS_2) + 40% (80% Fe·20% Pt)				Compounded but not hot-pressed.
493	40% (75% TiO_2·25% MoS_2) + 60% (80% Fe·20% Pt)				Compounded but not hot-pressed.
494	20% (75% TiO_2·25% MoS_2) + 80% (80% Fe·20% Pt)				Compounded but not hot-pressed.
495	80% (75% MoS_2·25% MoS_2) + 20% (80% Fe·20% Pt)				Compounded but not hot-pressed.
496	60% (75% MoS_2·25% TiO_2) + 40% (80% Fe·20% Pt)				Compounded but not hot-pressed.
497	40% (75% MoS_2·25% TiO_2) + 60% (80% Fe·20% Pt)				Compounded but not hot-pressed.
498	20% (75% MoS_2·25% TiO_2) + 80% (80% Fe·20% Pt)				Compounded but not hot-pressed.
499	80% MoS_2 + 20% (90% Fe·10% Re)				Compounded but not hot-pressed.
500	60% MoS_2 + 40% (90% Fe·10% Re)				Compounded but not hot-pressed.
501	40% MoS_2 + 60% (90% Fe·10% Re)				Compounded but not hot-pressed.
502	20% MoS_2 + 80% (90% Fe·10% Re)				Compounded but not hot-pressed.
503	80% MoS_2 + 20% (90% Ti·10% Re)				Compounded but not hot-pressed.
504	60% MoS_2 + 40% (90% Ti·10% Re)				Compounded but not hot-pressed.
505	40% MoS_2 + 60% (90% Ti·10% Re)				Compounded but not hot-pressed.
506	20% MoS_2 + 80% (90% Ti·10% Re)				Compounded but not hot-pressed.
507	80% MoS_2 + 20% (90% Ni·10% Re)				Compounded but not hot-pressed.
508	60% MoS_2 + 40% (90% Ni·10% Re)				Compounded but not hot-pressed.
509	40% MoS_2 + 60% (90% Ni·10% Re)				Compounded but not hot-pressed.
510	20% MoS_2 + 80% (90% Ni·10% Re)				Compounded but not hot-pressed.
511	90% MoS_2 + 10% K-162B*	----	2040	370	
512	80% MoS_2 + 20% K-162B*	----	2080	660	
513	70% MoS_2 + 30% K-162B*	----	2100	1460	
514	30% MoS_2 + 70% K-162B*	----	2190	7930	Specimen brittle.

*Parts fabricated by vendor, pressing load not furnished.

TABLE XVI CONTINUED

SPECIMEN NO.	MATERIAL	PRESSING LOAD (psi)	MAXIMUM PRESSING TEMPERATURE	COMPRESSIVE FRACTURE LOAD (lbs)	REMARKS
515	20% MoS_2 + 80% K-162B*	----	2150	7890	
516 & 517					Duplicates of No. 389.
518 & 519					Duplicates of No. 327
520 & 521					Duplicates of No. 319.
522 & 523					Duplicates of No. 382.
524 & 525					Duplicates of No. 276.
526 & 577					Duplicates of No. 325.
528 & 529					Duplicates of No. 292.
530 & 531 & 531A					Duplicates of No. 292.
532 & 533					Duplicates of No. 381.
534 & 535					Duplicates of No. 331.
536 & 537					Duplicates of No. 351.
538 & 539					Duplicates of No. 323.
540	$MoSi_2$**	----	----	600	
541	TiB_2**	----	----	600	

*Parts fabricated by vendor, pressing load not furnished.

**Parts fabricated by the vendor, pressing load and temperature not supplied

TABLE XVII

MoS_2 DRY-PRESS DATA (ROOM TEMPERATURE)

Specimen No.	Pressing Load (psi)	After Press Treatment	Fracture Load (lbs)	Type of MoS_2
1	3080	--	16.7	Molykote Microsize
2	7700	--	26	"
3	15,400	--	50.4	"
4	61,600	--	134	"
5	92,500	--	165	"
6	61,600	--	--	Molykote Type Z
7*	61,600	Sintered at 1500°F in argon	--	Microsize
8	61,600	Sintered at 1800°F in argon	168.5	"
9	61,600	--	148	"
10 Note 1	61,600	--	150	"
11	61,600	--	80.5	"
12	61,600	--	121	"
13	185,000	Sintered at 1500°F in argon	179	"

TABLE XVII CONT.

Specimen No.	Pressing Load (psi)	After Press Treatment	Fracture Load (lbs)	Type of MoS_2
14	61,600	--	161.5	Microsize
15	7,700	--	30	"
16	61,600	Sintered at 1300°F in argon	135	"
17	61,600	Sintered at 1350°F in argon	146	"
18	116,000	--	161.5	"
19	139,000	--	270.0	"
20	139,000	--	294.5	"
21	116,000	Sintered at 1500°F in argon	150	"
22	116,00	Sintered at 1500°F in argon	150	"
23	92,500	"	108.5	"
24	139,000	"	159.0	"
25	162,000	"	262.5	"
26	147,000	--	265	"

TABLE XVII CONT.

Specimen No.	Pressing Load (psi)	After Press Treatment	Fracture Load (lbs.)	Type of MoS_2
27	154,000	--	297.5	"

*Failed from Thermal Shock during sintering.

NOTE 1. All specimens 10 through 27 made from MoS_2 dried in vacuum at 300°F prior to pressing.

TABLE XVIII

W.S.U. FRICTION AND WEAR TESTS-HIGH TEMPERATURE

MATERIAL: K-1628 vs. Lubricant Composites
SPEED: 7200 ft/min; Load, one pound; Temperature, 1500°F

Run No.	Pellet No. (Boeing)	Run Time (min)	Composition	Scar Area (in.^{2})	Fracture Strength (lbs)	Average Coefficient of Friction	Remarks
W-56	None	20	ATJ Graphite	0.0351		.22	Smooth very little oxidation of block.
W-57	None	40	ATJ Graphite	0.0496		.285	Smooth, very little oxidation of block.
W-58	None	40	ATJ Graphite	0.619		.26	Furnace burned out after 15 minutes of operation. Oxidation of block evident.
W-59	35	40	90% MoS_2 + 10% Ni	0.1059	740	.43	Excessive wear and oxidation of block. New furnace installed.
W-60	43	2	90% MoS_2 + 10%(50% Ti-50% Ni)		210		Pellet fractured before friction measurements could be made. Oxidation of block excessive.
W-61	23	3	89% MoS_2 + 1% Si + 10% Ni	0.1456	282.5	0.21	Wear and oxidation of pellet excessive.
W-62	28	3	80% MoS_2 + 10% Ni + 10% Graphite		410	0.29	Excessive wear and oxidation of pellet prior to fracture.
W-63	34	2	80% MoS_2 + 10% Ni + 10% Au	0.128	728	0.40	Wear of pellet excessive.
W-64	40	3	90% MoS_2 + 10% Fe		264	0.26	Pellet was brittle. Broke into several small pieces.
W-65	18	4	80% MoS_2 + 10% PbS + 10% Ni	0.129	584	0.41	Wear of pellet excessive.
W-66	26	2	85% MoS_2 + 5% PbO + 10% Ni	0.123	786	0.5	Wear of pellet excessive.
W-67	27	2	85% MoS_2 + 10% Ni + 5% $Pb_2(PO_4)_3$	0.111	924	0.50	Wear of pellet excessive prior to fracture.
W-68	44	2	90% MoS_2 + 10% (80% Cr-20% Ni)			0.40	Pellet appeared to be brittle and fractured.
W-69	46	2	90% MoS_2 + 10% (20% Cr-80% Ni)	.110	568	0.31	Wear of pellet excessive.
W-70	48	8	40% MoS_2 + 10% (50% Zr-50% Ni)	.133	200		Wear and oxidation of pellet excessive. Wire in strain gage circuit broke preventing friction measurement.
W-71	57	3	90% MoS_2 + 10% Cr			.36	Pellet appeared to be brittle and fractured.
None	21		80% MoS_2-10% Ag_2S + 10% Graphite		136		Pellet split while drilling hole for mounting in machine.
W-72	93	5	90% MoS_2 + 10% (42% Ni + 58% Al)	0.0438	800	0.36	Pellet Fractured; Wear Excessive.
W-73	83	5	90% MoS_2 + 10% Metco 43C	0.107	720	0.49	Pellet fractured; wear excessive.
W-74	99	40	90% MoS_2 + 10% (80% Fe + 20% Pt)	0.0838	1520	0.291	Pellet completed the 40 minute test.
W-75	96	13	90% MoS_2 + 10% (80% Fe + 20% Pd)	0.0763	1160	0.196	Wear excessive.
W-76	87	5	90% MoS_2 + 10% (60% Fe + 40% Cr)		1260	0.29	Pellet brittle at 1500°F; wear excessive.
W-77	91	0.25	90% MoS_2 + 10% (87% Ni + 13% Al)		580		Pellet fractured after 15 seconds. Pellet brittle at 1[illegible]°F.
W-78		40	ATJ Graphite 3/8"	0.068		0.207	Pellet Completed 40 minute test with less wear than other pellets.

TABLE XVIII CONTINUED

Run No.	Pellet No. (Boeing)	Run Time (min)	Composition	Scar Area (in^2)	Fracture Strength (lbs)	Average Coefficient of Friction	Remarks
W-79	187	3.5	20% NiO + 80% Ni	0.1628	5000	0.73	Wore excessively, did not last the desired 40 minutes.
W-80	192	7	10% MoS_2 + 10% TiO_2 + 80% Ni	0.1113	3860	0.36	Wore excessively, did not last the desired 40 minutes.
W-81	184	23	40% TiO_2 + 60% Ni	0.1395	3860	0.22	Wear was excessive, did not last 40 minutes.
W-82	144	40	80% MoS_2 +20% (80% Fe + 20% Pd)	0.0682	3430	0.17	Slight wear; pellet ran the desired 40 minutes.
W-83	176	2	50% MoS_2 + 50% TiC	0.1265	2800	0.39	Wore excessively after 8 minutes of testing.
W-84	175	16	40% moS_2 + 60% TiC	0.1229	3000	0.35	Wore excessively after 16 minutes of testing.
W-85	170	40	10% MoS_3 + 90% (60% Fe + 40% Cu)	0.1170	6000	0.25	Test ran the desired 40 minutes although wear was excessive.
W-86	159	40	50% MoS_2 + 50% (80% Fe + 20% Pt)	0.1186	3900	0.24	Test ran the desired 40 minutes although wear was excessive.
W-87	196	20	20% MoS_2 + 80% (60% Ni + 40% Cu)	0.1531	8000 +	0.1531	Wore excessively after 20 minutes of testing.
W-88	204	25	40% MoS_2 + 60% (80% Fe + 20% Pt)	0.067	8000 +	0.27	Pellet fractured after 25 minutes of testing. Up to this time wear was not excessive.
W-89	197	25	40% MoS_2 + 60% (80% Fe + 20% Pd)	0.0922	8340	0.28	Wore excessively after 25 minutes of testing.
W-90	193	3	80% Ni + 15% TiO_2 + 5% NiO	0.1728	8000+	0.41	Wore excessively after only 3 minutes of testing.
W-91	145	17	75% MoS_2 + 25% (80% Fe + 20% Pd)	0.0841	2200		Vibration in the test-rig was excessive preventing accurate measurement of friction coefficients.

TABLE XIX

WASHINGTON STATE UNIVERSITY FRICTION AND WEAR TESTS - ROOM TEMPERATURE

Material: K - 162B against ATJ Graphite
Speed: 7200 ft/min.

Run No.	Run Time (min.)	Load (lbs)	Scar Width (in)	Scar Area (in^2)	Coefficient of Friction Minimum	Coefficient of Friction Maximum	Remarks
W-51	20	1	.068	.034	.42	.52	Test stopped when circuit breaker was thrown
W-52	15	1/2	.054	.027	.350	.45	The test pellet vibrated loose at 1/2 lb. load.
W-53	20	1/2	.0625	.313	.320	.340	Same as above
W-54	18	1	.063	.315	.185	.250	Air line broke releasing load on pellet
W-55	40	1	.094	.047	.150	.175	Satisfactory Operation

TABLE XX

BOEING FRICTION AND WEAR TESTS–ROOM TEMPERATURE

Specimen Number	Specimen Weight, Grams Before	After	Loss	Test Duration	Wear Scar Width, In.	Coefficient of Friction Initial	High	Low	Remarks
48	3.4160	3.1347	0.2813	10 min.	Full Width	0.14	0.14	0.02	Low F_c at 4 minutes.
57	3.2520	2.9205	0.3315	10 min.	Full Width	0.08	0.08	0.03	F_c erratic, gradual increase last 5 minutes.
83	4.2784	4.0070	0.2714	10 min.	Full Width	0.09	0.09	0.03	Gradual F_c decrease during test; pellet wear scar is very shiny.
87	3.9348	3.6067	0.3281	10 min.	Full Width	0.11	0.11	0.07	F_c showed gradual decrease during run.
93	3.1720	2.9670	0.2050	10 min.	Full Width	0.10	0.10	0.07	F_c constant at 0.07 after 6 minutes.
96	3.7304	3.2425	0.4879	10 min.	Full Width	0.09	0.09	0.01	F_c dropped to 0.01 at 3 minutes and remained constant.
97	4.0051	3.8076	0.1975	10 min.	Full Width	0.10	0.14	0.08	Low F_c at end of run.
ATJ Graphite	1.7190	1.7170	0.0020	10 min.	0.16 (30%)	0.23	Constant		Test run at 1 pound.
ATJ Graphite	1.7347	1.7325	0.0022	10 min.	0.15 (35%)	0.076	Constant		Test run at 3 pounds.
ATJ Graphite	1.6158	1.6129	0.0029	10 min.	0.17 (35%)	0.11	0.40	0.11	Gradual rise of F_c during test.
185	5.1250	5.0502	0.0748	10 min.	0.30 (80%)	0.14	0.165	0.14	F_c nearly constant throughout test.
AMP 10220-500-1B	1.7585	1.7544	0.0041	10 min.	0.18 (45%)	0.064	0.122	0.064	Gradual rise of F_c during test.
291	3.8616	3.6700	0.1916	10 min.	Full Width	0.11	0.11	0.11	Fairly constant F_c throughout test.
292	6.2098	6.0096	0.2002	10 min.	0.35	0.14	0.15	0.13	F_c erratic between high and low values.
293	9.5894	9.4617	0.1277	1 min.					Could not obtain a F_c reading due to chatter; apparently a high F_c; rapid wear - galling.
144	5.4294	5.3149	0.1145	10 min.	0.29 (85%)	0.19	0.20	0.19	F_c fairly constant.
197	6.1725	5.9356	0.2369	10 min.	Full Width	0.23	0.30	0.20	Chattered during first 2 minutes of test.
203	5.8777	5.4635	0.4142	10 min.	Full Width	0.38	0.38	0.22	F_c erratic.
204	5.8194	5.5364	0.2830	10 min.	Full Width	0.28	0.28	0.20	Gradual decrease of F_c during test.
209	2.8366	2.6773	0.1593	10 min.	0.33 (0.90%)	0.26	0.33	0.23	Tended to chatter and developed considerable heat.
214	5.1056	4.9663	0.1393	10 min.	0.20	0.31	0.31	0.11	Tended to chatter and erratic F_c.
262	3.6684	3.1627	0.5057	10 min.	0.25	0.22	0.26	0.19	Shoulder chipped off.
263	4.3954	4.2956	0.0998	10 min.	0.30	0.15	Nearly Constant		Corners chipped.
276	4.2653	4.0017	0.2636	2.5 min.	——	0.31		0.17	Off at 2 - 1/2 minutes due to chatter.
ATJ Graphite + B_2O_3	1.5364	1.5326	0.0038	10 min.	0.12 (0.048)	0.04	Constant		Little difference between treated and untreated.
ATJ Graphite Not Treated		Not Weighed		10 min.	0.14 (0.045)	0.09	Constant		
AMP P/N 10220-500-1A (Heat Treated)	1.7476	1.7397	0.0079	10 min.	0.19 (0.059)	0.10	0.10	0.08	F_c nearly constant.
MY 3F	2.7164	2.7137	0.0027	10 min.	0.13 (0.040)	0.06	0.06	0.055	Constant at 0.055 after 1 minute.
MY 9D	2.4565	2.4526	0.0039	10 min.	0.15 (0.055)	0.05	0.05	0.05	Some vibration.
Pyro. No. 1	2.1019	2.0950	0.0069	10 min.	0.19 (0.062)	0.09	0.09	0.05	F_c constant at 0.05 after 2 minutes.

TABLE XX CONTINUED

Specimen Number	Specimen Weight, Grams Before	After	Loss	Test Duration	Wear Scar Width, in.	Coefficient of Friction Initial	High	Low	Remarks
Pyro. No. 2	2.1990	2.1862	0.0128	10 min.	0.22 (0.084	0.14	0.18	0.10	F_c fluctuated, showed general rising trend.
EY 9106	1.5845	1.5797	0.0048	10 min.	0.18 (0.068	0.09	0.11	0.08	
$MoSi_2$ + Graphite	1.7519	1.7452	0.0067	10 min.	0.20 (0.060)	0.07	0.14	0.07	Gradual rise in F_c; considerable vibration; pellet contained lumps or crystals of hard abrasive material.
TiB_2 + Graphite	1.6129	1.6096	0.0033	10 min.	0.15 (0.052	0.13	0.13	0.08	Considerable vibration; smooth wear track.
116	3.3635	3.3424	0.0211	10 min.	0.20 (0.080)	0.11	0.13	0.11	Vibration and tended to grab.
415	3.8778	3.8674	0.0104	10 min.	0.18 (0.061)	0.13	Constant,	± 0.01	Some vibration; F_c somewhat erratic.
418	2.0688	2.9511	0.0177	10 min.	0.18 (0.070)	0.12	0.14	0.12	F_c showed slight gradual increase.
446	4.2780	4.2304	0.0476	10 min.	0.25 (0.103)	0.14	Constant		Vibration during first half of test.
511	3.2108	3.0348	0.1760	10 min.	0.38 (97%)	0.15	0.15	0.08	Gradual decrease in F_c.
512	2.8551	2.7778	0.0773	10 min.	0.27 (60%)	0.17	0.17	0.11	Gradual decrease in F_c.
513	3.9504	3.9065	0.0439	10 min.	0.25 (55%)	0.09	Constant		
514	4.5652	4.5132	0.0520	5 min.	Indeterminate	0.17	0.50	0.12	Off at 5 minutes due to chatter and intermittent grabbing.
515	4.5250	4.335	0.1915	10 min.	0.33 (0.85%)	0.25	0.50	0.16	Chattered during first two minutes of test.
Unknown	2.5060	2.4881	0.1079	10 min	0.36 (95%)	0.18	0.16	0.13	Fairly constant F_c after 1 minute at 0.13
283	4.1258	3.6185	0.5073	10 min.		0.15	0.22	0.15	F_c showed gradual increase
284	5.6201	5.4021	0.2180	10 min.		0.17	0.17	0.108	Low F_c at 3 min., gradual increase to F_c = 0.16 at 10 minutes.
285	5.7280	3.9270	1.8010	1 min.		0.4 to	0.5	----	Off at 1 minute due to high wear and friction.
286	----	----	----	----		----	----	----	Not run; too soft.
275	----	----	----	----	----	----	----	----	Not run; too soft.
287	----	----	----	----	-	----	----	----	Not run; too soft.
289	6.5110	5.4549	0.0561	1 min.		0.4	0.5	----	Off at 1 minute due to hear wear and friction.
290	4.7666	4.5364	0.2302	10 min.		0.13	0.26	0.13	F_c gradual rise during test.
190	5.5009	5.4509	0.0500	10 min.		0.19		0.12	F_c nearly constant over last 9 minutes of run.
269	7.0738	6.5745	0.4993	1 min.					Could not obtain F_c reading due to chatter; test stopped at 1/2 minute.
184	4.7867	4.7366	0.0501	10 min.		0.14	0.17	0.14	F_c nearly constant throughout run.
156	3.3636	3.1015	0.2821	10 min.		0.11	0.33	0.11	Considerable chatter, F_c rose gradually; unsatisfactory.
167	3.2510								
139	3.5657								
145	3.5470	3.5049	0.0421	10 min.		0.08	0.08	0.05	F_c constant
152	4.4470	3.9006	0.5464	10 min.		0.09	0.13	0.09	Mirror finish on pellet; gradual increase in F_c (F_c = 0.05 at 1800 rpm).
169	1.2459	1.2287	0.0172			0.12	0.116	0.056	

TABLE XX CONTINUED

Specimen Number	Specimen Weight, Grams Before	After	Loss	Test Duration	Wear Scar Width, In.	Coefficient of Friction Initial	High	Low	Remarks
189	1.8963	1.6191	0.2772	10 min.		0.16	0.25	0.16	F_c showed steady, gradual increase.
198	5.8562	5.8007	0.0555	6 min.		0.14	----	----	F_c fairly constant but test stopped at 6 minutes due to chatter.
207	3.2521								
44	2.9832	2.7872	0.1960	1 min.		0.14	0.2	0.14	Off at 1 minute due to high wear.
46	3.4830	3.1762	0.3068	10 min.	Full Width	0.17	Constant over full 10 minutes.		High wear.

Aeronautical Systems Division, Dir/Aeromechanics, Flight Dynamics Lab, Wright-Patterson AFB, Ohio.
Rpt Nr ASD-TDR-62-1057, DEVELOPMENT OF DESIGN CRITERIA FOR A DRY FILM LUBRICATED BEARING SYSTEM. Final Report, Mar 63, 142p. incl illus., tables.

Unclassified Report

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In Phase I, dry film lubricated plain, ball and roller bearings were tested in 900°F air at 15,000 rpm. Two different bearing designs,

(over)

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2. Lubrication friction and wear
3. Ball bearings
4. Roller bearings
5. Dry film lubricants.

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IV. M. E. Campbell, J. W. Van Wyk
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which used unconventional dry film lubrication techniques, demonstrated the feasibility of operation at 15,000 rpm in 900°F air.

In Phase II, roller and ball bearings were evaluated through the temperature range 70 to 1500°F at 15,000 rpm in a vacuum. An investigation was initiated to develop new lubricant composite materials for dry film lubrication under vacuum conditions.

Conception of a new and unique bearing design utilizing a lubricant composite material as the cage resulted in successful vacuum operation for both ball and roller bearings.

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